CHEMICAL ENGINEERING TRANSACTIONS
VOL. 33, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791
DOI: 10.3303/CET1333118

Condition Monitoring of Shinkansen Tracks Based on Inverse Analysis

Takahito Kobayashi*[a], Yasukuni Naganuma[b] and Hitoshi Tsunashima[c]

[a] Graduate School of Nihon University, 1-2-1 Izumi-cho, Narashino-shi Chiba, Japan
[b] Nippon Kikai Hosen KK., 2-1-95 Kounan, Minato-ku Tokyo, Japan
[c] Nihon University, 1-2-1 Izumi-cho, Narashino-shi Chiba, Japan
cita12014@g.nihon-u.ac.jp,

This paper demonstrates the possibility to estimate the track irregularities of Shinkansen tracks using car-body motions only. In an inverse problem to estimate track irregularity from car-body motions, a Kalman Filter (KF) was applied to solve the inverse problem. Estimation results showed that track irregularity estimation in vertical direction is possible with acceptable accuracy for real use.

1. Introduction

Track irregularity deteriorates ride comfort and running safety, track condition monitoring for maintenance is one of the most important tasks for railway companies. In general, track irregularity is measured several times a month by a specially designed track geometry car. In 2009, the track condition monitoring system called RAIDARSS started operation in the Tokaido Shinkansen line. Inertial measurement devices are mounted on six N700 Shinkansen train set and they measure the track several times a day. However, RAIDARSS needs high frequent maintenance because accelerometers are mounted on axle-boxes of vehicles. If the track irregularity in level can be estimated from car-body acceleration of in-service vehicle, it will enable high frequent track condition monitoring by a portable device (Tsunashima *et. al*., 2012).
This study proposes the track irregularity estimation techniques from car-body motion only. The inverse analysis technique is applied to estimate the track irregularity. This technique is frequently utilized to determine an unknown input signal (track irregularity) from a known output signal (car-body acceleration).

2. Construction and validity of vehicle model

2.1 Vehicle model

Figure 1 shows a railway vehicle model in vertical direction. Where z_c is a car-body displacement, z_{t1} and z_{t2} are front and rear bogie displacement, θ_c is a car-body pitch angle, θ_{t1} and θ_{t2} are front and rear bogie pitch angle. Inputs, r_{1a},r_{1b},r_{2a},r_{2b}, denote the track irregularities. The equation of motion for 6 DOF railway vehicle traveling on a straight track can be written as

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

where $\boldsymbol{Z}^T(t)=[z_c\ l_c\theta_c\ z_{t1}\ l_{t2}\theta_{t1}\ z_{t2}\ l_{t2}\theta_{t2}]$, $\boldsymbol{r}^T(t)=[r_{1a}\ r_{1b}\ r_{2a}\ r_{2b}]$. Coefficient matrices of the equations (1) are shown in the appendix.
The vehicle model was constructed using the discrete state-space model. The state equation and the measurement equation are expressed by

$$\boldsymbol{x}_n=\boldsymbol{F}\boldsymbol{x}_{n-1}+\boldsymbol{B}\boldsymbol{u}_n+\boldsymbol{G}\boldsymbol{w}_n\,, \tag{2}$$

$$\boldsymbol{y}_n=\boldsymbol{H}\boldsymbol{x}_n+\boldsymbol{v}_n\,, \tag{3}$$

where $\boldsymbol{x}_n$, $\boldsymbol{u}_n$, $\boldsymbol{y}_n$ are the state vector, the input vector and the output vector, respectively. $\boldsymbol{w}_n$ and $\boldsymbol{v}_n$ are process noise and measurement noise.

Please cite this article as: Kobayashi T., Naganuma Y., Tsunashima H., 2013, Condition monitoring of shinkansen tracks based on inverse analysis, Chemical Engineering Transactions, 33, 703-708 DOI: 10.3303/CET1333118

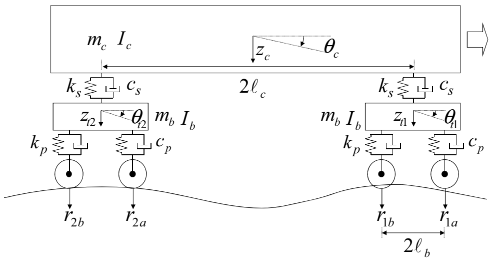
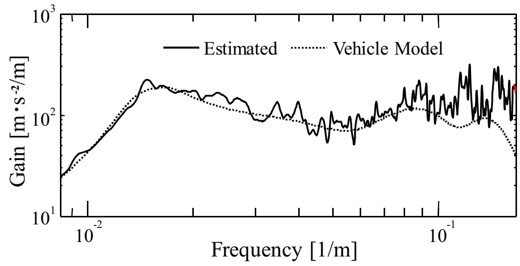


Figure 1: Railway vehicle model



(a) Gain

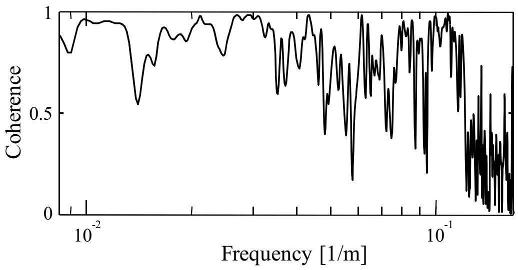
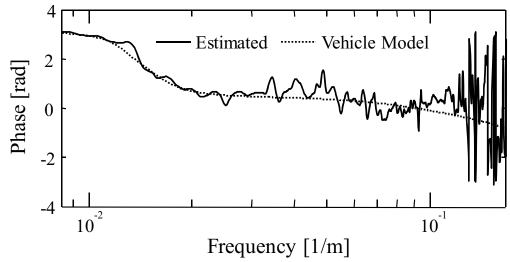


Figure 2: Coherence



(b) Phase

Figure 3: Frequency response functions

2.2 Frequency response functions and system identification

To confirm a validity of the simple model and parameter identification, frequency analysis was carried out. In the input and output relations of vertical direction, input is track irregularity, and output is car-body acceleration.

Figure 2 shows the coherence of track irregularity and car-body acceleration. This relation shows strong correlation, thus it can be assumed the dynamics as linear system. Figure 3 shows the frequency response functions of gain characteristic and phase characteristic. Dotted line given in Figure 3 indicates the frequency response function calculated with the vehicle model, and solid line is estimated from measured track irregularity and car-body acceleration. There is good correspondence between the estimated and the calculated values. It demonstrates that the model and parameters are appropriate.

3. Track irregularity estimation technique

Two approaches for inverse analysis are applied in this study. First approach focuses on the impulse response of the vehicle, and second one uses a new state equation of a simplified vehicle model. Details of each method will be discussed in next section. Figure 4 shows the flow of inverse analysis using a KF.

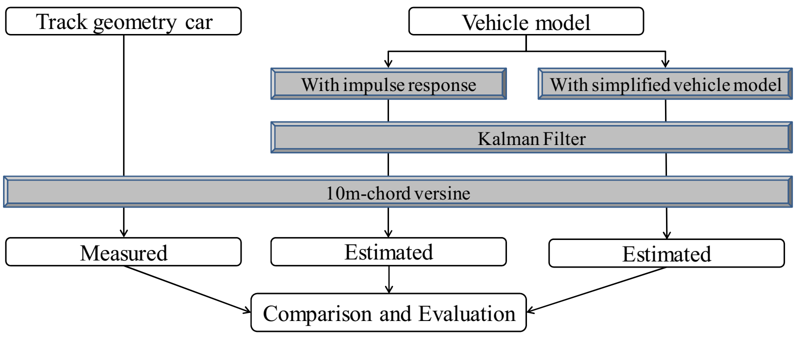


Figure 4: KF based signal-processing methods

In this study, to confirm the validity of theoretical inverse analysis, we carried out the following steps.

(Step 1) Generate a random number, and create the track geometry data (more than 6m wavelength) that is similar to the frequency characteristics of the actual track.

(Step 2) Calculate the car-body acceleration and car-body pitch rate using the track geometry data.

(Step 3) Add a Gaussian noise to vehicle motion, and it is used as the measurement data.

(Step 4) Estimate the track geometry from measurement data using a KF.

(Step 5) Compare the track geometry.

A KF approach is a well-known estimation technique proposed in various fields. The track irregularities are estimated from the measured car-body acceleration containing noise. The KF based estimation algorithms can be written as

<u>Time update equations</u>

$$\boldsymbol{x}_{n|n-1} = \boldsymbol{F}\boldsymbol{x}_{n-1|n-1} + \boldsymbol{G}\boldsymbol{u}_n \,, \tag{4}$$

$$\boldsymbol{P}_{n|n-1} = \boldsymbol{F}\boldsymbol{P}_{n-1|n-1}\boldsymbol{F}^T + \boldsymbol{G}\boldsymbol{Q}\boldsymbol{G}^T \,, \tag{5}$$

<u>Measurement update equations</u>

$$\boldsymbol{K}_n = \boldsymbol{x}_{n|n-1}\boldsymbol{H}^T\left(\boldsymbol{H}\boldsymbol{P}_{n|n-1}\boldsymbol{H}^T + \boldsymbol{R}\right)^{-1}, \tag{6}$$

$$\boldsymbol{x}_{n|n} = \boldsymbol{x}_{n|n-1} + \boldsymbol{K}_n\left(\boldsymbol{y}_n - \boldsymbol{H}\boldsymbol{x}_{n|n-1}\right), \tag{7}$$

$$\boldsymbol{P}_{n|n} = \boldsymbol{P}_{n|n-1} - \boldsymbol{K}_n\boldsymbol{H}\boldsymbol{P}_{n|n-1} \,, \tag{8}$$

where $\boldsymbol{x}_{n|n}{}^T = [\, x_n \;\; x_{n-1} \cdots \;\cdots \; x_{n-L+1} \,]$ is the track irregularities, and $\boldsymbol{y}_n{}^T = [\, y_n \;\; y_{n-1} \cdots \;\cdots \; y_{n-L+1} \,]$ is the car-body acceleration. $\boldsymbol{Q}$ is the covariance matrix of process noise. $\boldsymbol{R}$ is the covariance matrix of measurement noise. In a conventional state equation, the external input $\boldsymbol{u}_n$ 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 the random walk model with the external input and the process noise. The state transition matrix $\boldsymbol{F}$ of the equation (2) can be shown as

$$\boldsymbol{F} = \begin{bmatrix} 0 & \cdots & \cdots & \cdots & 0 \\ 1 & \ddots & \ddots & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & 1 & 0 \end{bmatrix}.$$

4. Estimation of track irregularities

In this study, we are focusing on the 10m-wavelength track irregularity that affect the running safety. Transformation of the 10m-chord versine method by actual track geometry can be approximated by $x(l) = y(l) - (y(l+5) + y(l-5))/2$, where $y(l)$ represents the track geometry, and $x(l)$ represents the 10m-chord versine.

4.1 Estimation using impulse response

In this section, a estimation technique using the impulse response of the vehicle (Figure 5) is evaluated. The impulse response can be obtained by giving an impulse input to equation (2) and (3). When applying an impulse response to inverse analysis, the observation matrix $\boldsymbol{H}$ of equation (3) can be given as $\boldsymbol{H} = [\, h(L) \quad h(L-1) \quad \cdots \quad \cdots \quad h(0) \,]$. The symbol h denotes the impulse response, and the symbol L denotes the total number of impulse response (Kobayashi *et. al.*, 2012).

Figure 6 shows the estimation results. The track geometry and 10m-chord versine can be estimated with good accuracy with the actual data. The maximum estimation error is about 1.5mm. The result revealed that the method is effective for track condition monitoring with acceptable accuracy.

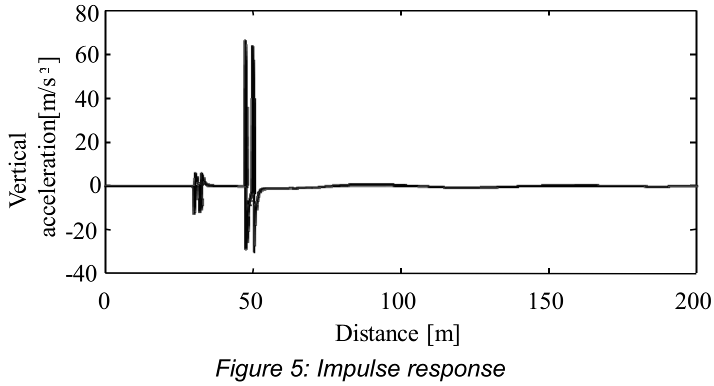
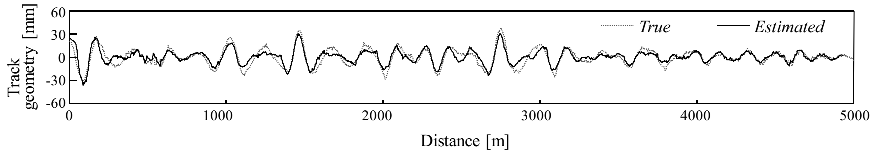
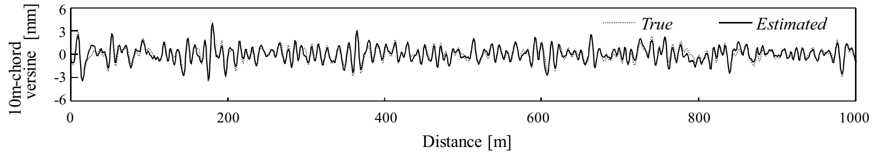


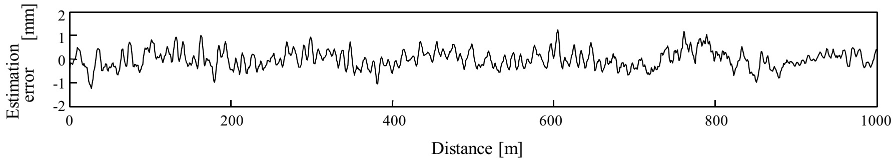
Figure 5: Impulse response



(a) Track geometry



(b)10m-chord versine



(c)Estimation error

Figure 6: Simulation results

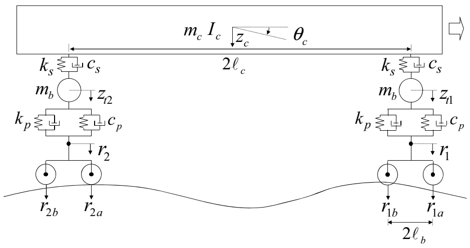


Figure 7: Simplified vehicle model

4.2 Estimation using a simplified vehicle model

The forward analysis of vehicle model gives the 8 inputs (track geometry of 4 axes and its differential value). But it is impossible to calculate back all these correctly with the inverse analysis. To develop a numerical model for inverse analysis, the following two assumptions were made for simplification (Naganuma *et. al.*, 2009).

(a) In practice, track irregularity is managed using 10m-chord versine whose wavelength bandwidth of 5 m to 100 m for running stability. Precisely, the vertical car-body acceleration does not contain frequency components correspond to the wavelength of twice of the wheel base of the bogie. Therefore, it is good enough for track management to know the average of irregularities at the front and rear wheel of the bogie.

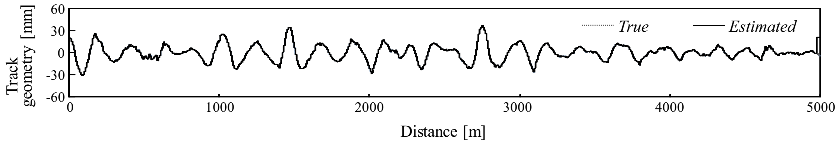
(b) A vehicle model is not necessary to express the pitching motion of bogies because the purpose is to estimate the track irregularity from the car-body acceleration.

Simplified vehicle model for inverse analysis is shown in Figure 7. In the previous section, the track geometry is expressed by the random walk model ($\boldsymbol{u}_{n+1}=\boldsymbol{u}_n+\boldsymbol{e}_n$), and it is shown that the KF based algorithm can be applied to the inverse analysis (Naganuma *et. al.*, 2012). In this approach, the external force vector (first-order differentiation of the track geometry) is included in the state vector. The state-space model can be written as

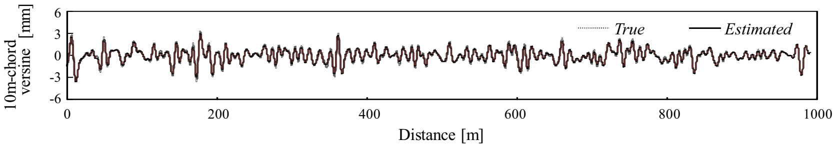
$$\begin{bmatrix} \boldsymbol{x}_{n+1} \\ \boldsymbol{u}_{n+1} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F} & \boldsymbol{B} \\ \boldsymbol{O} & \boldsymbol{\Omega} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_n \\ \boldsymbol{u}_n \end{bmatrix} + \begin{bmatrix} \boldsymbol{I} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{I} \end{bmatrix} \begin{bmatrix} \boldsymbol{w}_n \\ \boldsymbol{e}_n \end{bmatrix}, \quad (9)$$

$$\boldsymbol{y}_n = \begin{bmatrix} \boldsymbol{H} & \boldsymbol{O} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_n \\ \boldsymbol{u}_n \end{bmatrix} + \boldsymbol{v}_n, \quad (10)$$

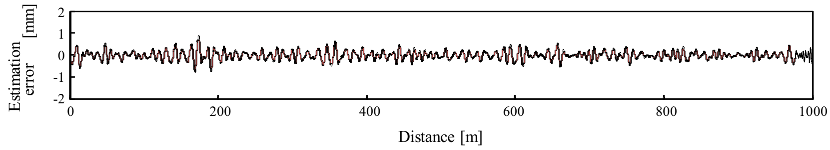
where $\boldsymbol{\Omega}$ is the unit vector. The track geometry can be estimated by this state-space model (9) and (10), and it is estimated to continuously and stably as one-component of the state vector. This model observes the pitch rate and the acceleration of car-body. Figure 8 shows the estimation results using the simplified model. The maximum estimation error is about 1.0mm. The result revealed that the KF is effective for track condition monitoring with acceptable accuracy as with the impulse model.



(a) Track geometry



(b) 10m-chord versine



(c) Estimation error

Figure 8: Simulation results

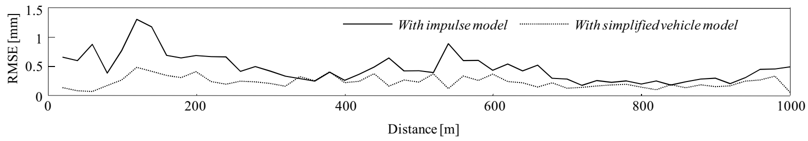


Figure 9: RMSE of the estimation results

5. Evaluation of the estimation results

5.1 RMSE (Root Mean Square Error)

In this section, RMSE of 20m section based on the result of 10 m-chord versine is calculated. The RMSE is an index evaluate the difference between the true value and the estimated value. It can be written as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X - x_i)^2}{N}}, \tag{11}$$

where X is the true value, x_i is the measured value, and N is the number of the data. Figure 9 shows the RMSE evaluation of the estimation results. The results showed that the method with simplified vehicle has better performance than the method with impulse response.

5.2 MPC metrics

In this section, we evaluated the estimation results of 10m-chord versine using the Sprague & Geers Metrics method (Ray *et. al.*, 2008). This method calculate the MPC metrics using the Sprague & Geers correlation function. The MPC metrics treats the two waves magnitude and phase. The magnitude component M should be sensitive to difference in magnitude. The phase component P should be sensitive to difference in phasing. 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 1 shows the equations of each component and calculation results. The symbol e_i and m_i in the equation represents the estimated values and true values. Table 1 data indicate that there is a high correlation between the true value and estimated value.

Table 1: MPC metrics

	Magnitude	Phase	Combination
Equations	$M = \sqrt{\frac{\sum e_i^2}{\sum m_i^2}} - 1$	$P = \frac{1}{\pi}\cos^{-1}\frac{\sum e_i m_i}{\sqrt{\sum e_i^2 \sum m_i^2}}$	$C = \sqrt{M^2 + P^2}$
With impulse response	0.082	0.072	0.109
With simplified vehicle model	0.075	0.060	0.096

6. Conclusion

In this paper, the track irregularities estimation techniques from car-body acceleration and/or pitch rate are proposed. Main results of the study are:

(a) The track geometry expressed by the random walk model, can be applied to the inverse analysis with KF formulation.
(b) The KF was used to estimate longitudinal level irregularity from car-body motion. The results confirmed that this filter can be used to calculate back the track irregularity with accuracy sufficient for track condition monitoring.

The proposed methods can be applied for the on-board condition monitoring device because they have real-time processing algorithm with the consideration of vehicle speed change.

References

Kobayashi, T., Naganuma, Y. and Tsunashima, H., 2012, Condition Monitoring of Shinkansen Tracks Based on Vehicle Model, The 6thInternational Symnosium on Speed-up, Safty and Service Technology for Railway and Maglev Systems, Korea.

Naganuma, Y. and Yoshimura, A., 2009, Reconstruction and estimation of railway track geometry using regularization methods, Proceedings of IAVSD, Stockholm, Sweden.

Naganuma, Y., Kobayashi, T. and Tsunashima, H., 2012, Study on track geometry estimation from car-body acceleration, The 19th Jointed Railway Technology Symposium,No.12-79.187-190.

Ray, M. H., Anghileri, M. and Mongiardini, M., 2008, Comparison of validation metrics using repeated Full-scale automobile crash tests, WCCM 8, Venice, Italy.

Tsunashima, H., Naganuma. Y., Matsumoto, A., Mizuma, T. and Mori, H., 2012, Condition Monitoring of Railway Track Using In-Service Vehicle, Reliability and Safety in railway, Intech, 333-356.

Appendix : Coefficient matrices in Eq. (1)

Equations of motion of the vehicle model in vertical direction can be written as follows

$$\boldsymbol{M} = \mathrm{diag}\left[m_c \;\; I_c/l_c^2 \;\; m_{t1} \;\; I_{t1}/l_{t1}^2 \;\; m_{t2} \;\; I_{t2}/l_{t2}^2\right],$$

$$\boldsymbol{C} = \begin{bmatrix} 2c_s & 0 & -c_s & 0 & -c_s & 0 \\ 0 & 2c_s & -c_s & 0 & c_s & 0 \\ -c_s & -c_s & 2(c_p+c_s) & 0 & 0 & 0 \\ 0 & 0 & 0 & 2c_p & 0 & 0 \\ -c_s & c_s & 0 & 0 & 2(c_p+c_s) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2c_p \end{bmatrix}, \quad \boldsymbol{K} = \begin{bmatrix} 2k_s & 0 & -k_s & 0 & -k_s & 0 \\ 0 & 2k_s & -k_s & 0 & k_s & 0 \\ -k_s & -k_s & 2(k_p+k_s) & 0 & 0 & 0 \\ 0 & 0 & 0 & 2k_p & 0 & 0 \\ -k_s & k_s & 0 & 0 & 2(k_p+k_s) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2k_p \end{bmatrix}$$

$$\boldsymbol{D} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ c_p & c_p & 0 & 0 \\ c_p & -c_p & 0 & 0 \\ 0 & 0 & c_p & c_p \\ 0 & 0 & c_p & -c_p \end{bmatrix}, \quad \boldsymbol{E} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ k_p & k_p & 0 & 0 \\ k_p & -k_p & 0 & 0 \\ 0 & 0 & k_p & k_p \\ 0 & 0 & k_p & -k_p \end{bmatrix}$$