Optimization of Suspension Under the Condition of Curved Track in Railway Vehicle

Jong Yoon Choi, Zheng Yuan Li, Seung Guk Baek, Ki Seok Song, Ja Choon Koo and Yeon Sun Choi†

Abstract

This paper presents the optimization of suspension characteristics under the condition of curved track railway vehicles. Reducing lateral acceleration on curved track is an issue for high-speed railway vehicles. In terms of curved track running environments, reducing the lateral vibration of railway vehicles is critical to safety and curving performance. The properties of lateral damping and stiffness of both primary and secondary suspension show effect on wheel-set, bogie and car-body. Analysis for reducing the lateral vibration of rail vehicles with respect to the characteristics of both primary and secondary suspension has been developed using ADAMS/Rail. Response Surface Method has been chosen for the purpose of verifying correlation effects among design parameters. Also, this paper suggests the method for designing optimal suspension of railway vehicles on curved track. The optimization result indicates decrement of lateral acceleration on wheel-set by 3% and bogie by 1% on curved track. Finally, this paper comes to the conclusion that suspension system of railway vehicle (KTX I) is properly designed when regarding lateral vibration of railway vehicle on diverse curved track condition.

Keywords: Curved track, Lateral acceleration, Optimization, Response surface method, Suspension

1. Introduction

The properties of suspension system in railway vehicles do significantly influence the running safety and curving performance on the condition of curved track. A design strategy is suggests that enables an optimal design with respect to safety and curving performance. In general, stiffness of suspension system has been increased in order to assure safety in railway vehicles. However, it has disadvantage of decreasing the curving performance of railway vehicle. When it comes to designing the suspension system, considering both running safety and curving performance is critical in high speed railway vehicles. It is thus becomes more complex process when designing of suspension system as the speed of the vehicle increases.

Nishimura suggests designing method of suspension system that satisfy safety and stability of high speed train [1]. Optimization of suspension system was discussed by Matowicz on the purpose of safety [2]. A. Johnsson optimized a railway vehicle with respect to safety and running performance considering lateral damping of bogie system [3]. Designing method for suspension characteristics using neural network model and response surface model is suggested by Park [4]. Optimization of diverse design variables with regard to suspension system employing response surface method and neural network is developed by Park [5]. Similarly, we suggest design strategy for optimizing requirement of reducing lateral acceleration based on car body, bogie and wheel set under the condition of curved track. This paper presents organized optimal design method for suspension components affecting the lateral acceleration of railway vehicle on curved track.

The content covers as follows. Design specification of railway vehicle used in computational analysis is defined in section 2. Effects of various conditions for curved radius and speed on railway vehicle is covered in section 3. In this section transfer function of primary and second-
ary suspensions is discussed. In section 4, characteristics of lateral acceleration are discussed with the change of suspension system. Finally, optimal design procedure for reducing lateral acceleration of railway vehicle is suggest applying response surface method on the condition of curved track in section 5.

2. Simulation Model

2.1 Railway vehicle property

The developed railway vehicle model is validated using the dynamic simulation soft ADAMS/Rail. Design specification of railway vehicle computational model is based on Korean high speed train (KTX I). Design parameters of KTX I are summarized in Table 1.

Railway vehicle model is classified into 3 parts including car body and, front bogie and rear bogie. Each part is applied to build up main system of railway vehicle. Sub-system of railway vehicle is consists of some other parts such as spring, damping, bushing, gear box and bump stop. The bogie model of KTX I is shown in Fig. 1 including principal components used in a simulation test to determine suspension parameters. Our target parameters are 1st spring, 2nd spring and 2nd damper.

Lateral stiffness and damping are determined to key factors of design parameters. The specification of running track is summarized in Table 2. Three different curved tracks are used in order to analyze lateral acceleration of running vehicle. In this research, curve radius of 5000, 6000, 7000 m curved tracks are employed.

2.2 Simulation condition

The suspension systems are selected as design parameters that affect the dynamics performance of railway vehicle on curved track. The analysis is done within the range of 400 km/h at 50 km/h intervals including maximum speed. Stiffness of primary suspension, Stiffness and damping coefficient of Secondary suspension are determined as design parameters. Validation of lateral acceleration response is done with the variation of design parameters. In order to analyze dynamics behaviors of the railway vehicle, tangent track and three different curved tracks are used. In this case, curve radius of 5000, 6000, 7000 m curved tracks are involved. Total running distance is fixed as 1400 m and step size is 1000 for one railway vehicle.

3. Frequency Analysis of Excitation Source

3.1 Tangent track and Curved track

Multi-body dynamic simulation software Adams/Rail is employed for dynamic performance of railway vehicle according to running environment. Design specification of Korean high speed train is applied to dynamics simulation. Lateral acceleration of railway vehicle is shown as result on the basis of different running track by increasing the speed of railway vehicle until 400 km/h.

In this section, lateral acceleration of railway vehicle is treated focused on curved track. Since running on the curved track has drawback of increasing lateral acceleration of railway vehicle, reducing lateral acceleration of

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Table 1 Specification of railway vehicle’s suspension

<table>
<thead>
<tr>
<th>Index</th>
<th>Terms</th>
<th>Units</th>
<th>Input</th>
</tr>
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<tbody>
<tr>
<td>1st s/p</td>
<td>Longitudinal Stiffness</td>
<td>N/m</td>
<td>581,300</td>
</tr>
<tr>
<td></td>
<td>Lateral Stiffness</td>
<td>N/m</td>
<td>581,300</td>
</tr>
<tr>
<td></td>
<td>Vertical Stiffness</td>
<td>N/m</td>
<td>741,000</td>
</tr>
<tr>
<td>2nd s/p</td>
<td>Longitudinal Stiffness</td>
<td>N/m</td>
<td>151,600</td>
</tr>
<tr>
<td></td>
<td>Lateral Stiffness</td>
<td>N/m</td>
<td>151,600</td>
</tr>
<tr>
<td></td>
<td>Vertical Stiffness</td>
<td>N/m</td>
<td>616,000</td>
</tr>
<tr>
<td>2nd damper</td>
<td>Longitudinal damping</td>
<td>Ns/m</td>
<td>8,000</td>
</tr>
<tr>
<td></td>
<td>Lateral damping</td>
<td>Ns/m</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>Vertical damping</td>
<td>Ns/m</td>
<td>4,200</td>
</tr>
</tbody>
</table>

Table 2 Curve radius of running track

<table>
<thead>
<tr>
<th>Index</th>
<th>Curve Radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent track</td>
<td>0</td>
</tr>
<tr>
<td>Curved track</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>7000</td>
</tr>
</tbody>
</table>

Fig. 1 Design variables of railway vehicle
high speed train becomes critical matters with regard to running on the curved track.

Fig. 2 illustrates how design parameters describing curved radius influence the lateral acceleration of running vehicle. Decreasing curved radius leads to larger lateral acceleration on wheel set, bogie and car body over most of the velocity range. On the condition of curved radius 5000, 6000 m, lateral acceleration of wheel set sharply increase when running velocity above 300 km/h. Whereas, lateral acceleration of wheel set shows smaller acceleration compare to lateral acceleration of bogie system in terms of curved radius 7000 m track and tangent track.

The results represent that lateral acceleration of railway vehicle is susceptible to velocity increase in curved track condition compare to tangent track condition. On tangent track condition, lateral acceleration of car body tends to decrease while increasing velocity of railway vehicle.

### 3.2 Transfer function

Transfer function is considered for the purpose of analyzing major design parameters on the basis of safety and curving performance of railway vehicle. Note that relationship between two systems is assumed as linear form such as wheel set, bogie and car body. The results of Fig. 4 show that the primary and secondary suspension has significant influence on railway vehicle with respect to rail radius.

The system between car body and wheel set shows different frequency range compare to the system between wheel set and bogie. In the following analysis, primary suspension is located between wheel set and bogie also, secondary suspension is located between bogie and car
body. Table 3 summarized the major frequency component of transfer function. Magnitude of lateral vibration that transfers from bogie to car body is larger under the condition of 1 Hz frequency range. By contrast, large magnitude of lateral vibration that transfers from wheel set to bogie observed in the range of 50 to 300 Hz. Therefore, optimal design of secondary suspension is important in the matter of curved track running environment.

4. Characteristics of Suspension System

In this section, dynamic behavior of railway vehicle is shown with the variation of suspension characteristics by using multi-body dynamic simulation software ADAMS/Rail. Within the range of 10% variation of suspension properties, analysis of a railway vehicle is carried out regarding lateral acceleration. The behavior of railway vehicle is not regard as quasi-static state now that track irregularities are applied on track.

The following analysis illustrates how design parameters describing lateral stiffness and lateral damping influence the lateral acceleration of railway vehicle on curved track. The results show that the variation of lateral stiffness and damping of suspension has less of an effect on the bogie and car body than wheel set. Fig. 5 shows changing lateral stiffness of primary suspension has more impact on lateral acceleration of railway vehicle under the condition of curved track when running with the speed of 400 km/h. Fig. 6 shows changing lateral stiffness of secondary suspension has more impact on lateral acceleration of railway vehicle under the condition of curved track when running over 350 km/h vehicle speed. Fig. 7 shows changing lateral damping of secondary suspension has

<table>
<thead>
<tr>
<th>Curve radius (m)</th>
<th>Car body / Bogie</th>
<th>Bogie / Wheel set</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>0.79 Hz</td>
<td>122 Hz</td>
</tr>
<tr>
<td>6,000</td>
<td>0.73 Hz</td>
<td>53 Hz</td>
</tr>
<tr>
<td>7,000</td>
<td>0.79 Hz</td>
<td>66 Hz</td>
</tr>
<tr>
<td>Tangent track</td>
<td>0.84 Hz</td>
<td>255 Hz</td>
</tr>
</tbody>
</table>

**Table 3** Major frequency range of transfer function

![Fig. 5 Lateral stiffness of 1st spring](image1)

![Fig. 6 Lateral stiffness of 2nd spring](image2)
more impact on lateral acceleration of railway vehicle under the condition of tangent track rather than curved track.

The optimal design of suspensions for the purpose of minimizing the lateral vibration of railway vehicle is complex process that must simultaneously consider curved radius of track, vehicle speed and characteristics of suspension. Thus, section 5 will cover design strategy of both primary and secondary suspension on diverse curved track environments including tangent track environments.

5. Optimization of Suspension System

In this section, response surface model approaches are employed to understand how much variation of the suspension affects the lateral acceleration of railway vehicle. This procedure builds algebraic regression approximations of objective functions in the process of optimization. The main goal of this optimization process is to design suspension systems that take curved track into consideration. This methodology has strength in that weighted value of curved radius effect is applicable to objective function.

Clarifying main factors and performance that related with lateral acceleration of railway vehicle is needed. The relationship between levels of factor and response variables is expressed as polynomial regression equation so as to define design parameters for reducing lateral acceleration using response surface model. The response surface model is based on statistical analysis that has strength of dealing with multiple effects of diverse variables. Therefore, deciding optimal performance index is possible under certain combination of independent variables. Also, the response surface model allows to identify how the independent factors interacting each other. Approximate function is used since design parameters of railway vehicle show nonlinear relationship among them [7,8,9].

There exists critical speed of railway vehicle according to running environments including rail radius of track. Consideration of lateral acceleration issue is necessary on optimization steps. Thus, objective function reflects characteristic of track condition and speed of railway vehicle. It has advantage of applying weighted value on rail radius condition is possible. 3 design variables are defined followed by testing 5 levels of each factor within the range of 10 %.

In this research, response variable includes the lateral acceleration of railway vehicle and the response surface plot is constructed considering relation between primary and secondary suspension system. Steepest descent method is employed in the process of forming response surface plot. In this way, the optimization of suspension system comes to a conclusion on curved track situation.

Approximate estimation of second order polynomial regressive equation is expressed in eq. (1). Eq. (1) becomes objective function and quadratic polynomial as general solution.

\[ y = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} a_{ij} x_i x_j \]  

Where, \( x_1, x_2, x_3 \), denotes the design variables of primary spring, secondary spring, secondary damping in sequence. \( k \) is the number of design variables, \( a \) is the coefficient of variables result in optimization simulation.

To find stationary point of regressive equation summarized matrix form is shown in eq. (2) and eq. (3).

\[ y = A_0 + x A_1 + x^T A_2 x \]  

![Fig. 7 Lateral damping of 2nd damper](image)
Checking stationary point is required as there are possibilities of existence of optimized parameters in stationary point as eq. (4).

Fig. 8 shows the response surface plot result from interaction among design parameters. The lateral acceleration of railway vehicle is minimized under the condition of increasing lateral damping value of secondary suspension as much as 10%, decreasing lateral stiffness value of primary suspension as much as 10% and Increasing lateral damping value of secondary suspension as much as 10%. Summarized optimization result is shown in Table 4.

Optimized suspension parameters are applied to dynamics performance of railway vehicle on curved track using multi-body dynamic simulation software ADAMS/Rail. Fig. 8 illustrates that lateral acceleration is decreased by 3% at and 1% at bogie system.

6. Conclusion

The design problems of high speed railway vehicle in terms of curved track running environment are hard to solve with the object of satisfying performance index. Especially, the design of railway vehicle’s suspension system is critical matter as it has to do with safety problems due to lateral vibration arise on curved track running. Hence, proper designing of suspension system is required in order to reduce lateral acceleration of railway vehicle. In this paper, Response Surface Method is used for verifying relation between suspension and railway vehicle dynamics during running. 1st spring, 2nd spring, 2nd damper are considered and compared running in the tangent track and curved track. In the tangent track, the lateral displacement increase ratio is decreasing when velocity is increase. But in the curved track, the lateral displacement increase ratio is increasing when velocity is increase.

Also, optimal suspension design method is presented considering both rail radius condition and vehicle speed. When it comes to rail radius condition on curved track, applying weighted value is possible on the process.
Primary and Secondary suspension are chosen for design factors for the purpose of reducing lateral acceleration of railway vehicle. Frequency analysis is performed with the variation of rail radius and vehicle speed. Statistical approach using response surface model is proposed in dynamic design problem. The developed methodology is validated by multi-body dynamic software ADAMS/Rail.

Finally, applying optimized suspension system on railway vehicle on curved track leads to decrement of lateral acceleration on wheel set by 3% and bogie by 1%.

References