Simple Method for Analyzing Contact between Wheelset Members and Track Structures Using MBD

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In this study, we have constructed an efficient contact model between wheelset members and track structures to express contact phenomenon between them during a large-scale earthquake. In this model, contact detection points are set on the multi body vehicle model and the contact surfaces are defined on the track structures modeled by FEM. The contact force between them is calculated by the penalty method. In addition, we have incorporated the model into the numerical analysis program DIASTARS III that is able to simulate the railway vehicle behavior before and after derailment, and we have performed trial calculations using this program.

Keywords: contact model, dynamic interaction, multi body dynamics, finite element method, earthquake, derailment

1. Introduction

In Japan, as part of the effort to ensure vehicle running safety during a large-scale earthquake, a variety of studies are being undertaken on guard angles [1] that prevent vehicle derailment and on vehicle guiding devices [2] that prevent derailed vehicles from reaching neighboring lines or completely leaving the track. When developing or implementing such measures, it is important to have a clear understanding of: vehicle behavior during earthquakes, the specific structure of the reinforcement measures, design methods, efficiency, cost/benefit ratio, and order of priority for installation. In this regard, vehicle behavior leading up to the derailment of a vehicle and the efficiency of the guard angles, have already been clarified through full-scale vehicle tests on a vibration table and numerical analyses [1] [3]. Regarding vehicle behavior after derailment, only basic behavior has so far been being clarified, not through experiments, which are difficult to conduct, but through numerical analyses [4]. Little is therefore known about the influence on vehicle behavior of contact between individual vehicle components (e.g. wheelset members and car bodies) and railway structures (e.g. civil engineering structures and rails) [5]. On the vehicle side, measures are also being developed, such as various vehicle mounted anti-derailment devices [6], however, it is still necessary to establish a flexible numerical analysis method which can quantitatively evaluate the effect of these countermeasures.

Hence, with the aim of establishing a numerical analysis method for simulating vehicle behavior while factoring in contact between vehicle components and railway structures before, during and after derailment, work was conducted to develop an analysis method for evaluating vehicle behavior taking into account the contact between wheelset members and track structures during earthquakes and to investigate its practical applicability.

2. Analysis method

FEM analysis is normally used for precise evaluation of contact problems in which the shape and size and non-linear characteristics of the material of the contact bodies are taken into consideration. This study however focuses on a complicated contact problem with multiple degrees of freedom, therefore, such an analysis would require large degrees of freedom if shell and solid elements were used. In addition, this study seeks to evaluate phenomena over a long period of several tens of seconds during which the running vehicle is derailed due to huge external forces such as an earthquake and comes into contact with railway structures. A practical analysis method is required to conduct this type of analysis. As such, the new analysis method in this study aims to practically express contact phenomena between vehicles and railway structures based on the following premises:

(1) In order to examine the contact phenomena between vehicles and railway structures efficiently, the contact phenomena occurring due to elastoplastic deformation will be investigated from a macroscopic angle, with a reasonable level of accuracy rather than taking a microscopic approach.

(2) Only vertical and perpendicular contact forces to the rail direction are considered. Furthermore, only the response force on the railway structures will be considered for contact force in the rail direction. Therefore, vehicles will be assumed to have linear uniform motion. Frontal collisions and deceleration will not be
(3) Contact forces will be efficiently calculated using penalty methods. Contact forces will be calculated between contact detection points set on vehicles modeled by multi body and contact surfaces set on railway structures modeled by finite elements.

(4) Contact (penalty) springs will be defined as the relationship between relative displacement (i.e., virtual penetration of contact detection points into contact surfaces) and contact force. Therefore, the contact spring will be expressed as a multi-linear model divided into sections. The characteristics of the contact spring will be separately clarified in element experiments or detailed FEM.

(5) Each contact spring will be defined according to the number of contact detection points, their location and intervals between them.

(6) The contact detection points on vehicles will be defined based on their location relative to the center of gravity of the multi-body assembly (carbody, bogie or wheelset) to which they belong.

(7) The contact surfaces on the railway structures will be defined using FE nodes.

An analysis method for contact between carbodies and railway structures has already been developed [7]. Therefore, this study aims to develop an analysis method for contact between wheelset members (gear boxes, brake discs and vehicle-mounted vehicle guidance devices, etc.) and track structures such as rails.

The method proposed in this study was developed by improving the numerical analysis program DIASTARS III [4], which is able to analyze dynamic interaction between vehicles and railway structures such as rails. In DIASTARS III, arbitrary structures can be modeled using a variety of finite elements. In this study, track members, a detailed dynamic model of which is discussed in Chapter 3, are also modeled using finite elements.

The equation of motion for vehicles in a vehicle coordinate system can be expressed as (1) by transposing non-linear spring terms between the vehicle components to the right-hand side.

\[
M' \ddot{X}'^T + C' \dot{X}'^T + K' X'^T = F'_L + F'_B (X', X'^T) + F'_V (X'^T)
\]  

where, superscript \( V \) and \( B \) represent the vehicle and the bridge (structure), respectively; \( X' \) and \( X'^T \) are displacement vectors of the vehicle and the structure, respectively; \( M', C' \) and \( K' \) are the mass, damping and stiffness matrices of the vehicle; \( F'_L \) is a load vector of centrifugal force, wind pressure and etc. on the vehicle; \( F'_B (X', X'^T) \) is the interaction load vector between the vehicles and railway structures; \( F'_V (X'^T) \) is the load vector of the vehicle model’s non-linear spring force that is handled as an external force.

### 2.2 Dynamic model of a railway structure

In DIASTARS III, arbitrary structures can be modeled using a variety of finite elements. In this study, track members, a detailed dynamic model of which is discussed in Chapter 3, are also modeled using finite elements.

The equation of motion for railway structures can be expressed as (2) by transposing non-linear spring terms to the right-hand side.

\[
M^b \ddot{X}^b + C^b \dot{X}^b + K^b X^b = F^b_L + F^b_B (X^b, X^b) + F^b_V (X^b)
\]  

where, \( M^b, C^b \) and \( K^b \) are the mass, damping and stiffness matrices of the railway structure, respectively; \( F^b_L \) is the load vector for earthquakes, wind pressure, etc. on the railway structure; \( F^b_B (X^b, X^b) \) is the interaction load vec-
tor between the vehicle and railway structure; \( F^e_s(X^e) \) is the load vector of the railway structure model’s non-linear spring force that is handled as an external force.

### 2.3 Contact model between a vehicle and a railway structure

Figure 2 shows the conceptual schematic of the contact model between a vehicle and a railway structure. To effectively express complex contact phenomena between a vehicle and a railway structure, the contact model uses contact detection points set on the vehicle and contact surfaces set on the railway structure. The contact surfaces are constructed on the basis of the information nodes from the railway structure FE model.

#### 2.3.1 Contact detection points on the vehicle

Contact detection points \( C_i \) \((i = 1, \ldots, n)\) are set on the vehicle at potential points of contact with railway structures. For each of these contact detection points, a judgment of contact or non-contact is made and the interaction force is calculated. When probable contact points on the vehicle can be predicted, contact detection points are set only on those points to improve the speed of contact calculation. When contact point cannot be predicted, contact detection points are set densely so that the contact point can be identified.

#### 2.3.2 Contact surfaces on a railway structure

Figure 3 shows the model of a contact surface on a railway structure. In this model, the contact surface \( \Gamma \) is divided into sections, each of which is determined by four points \( (E_1-E_4) \) on Line \( L_1 \) and \( L_2 \) running along the element borders. Dividing the contact surface into sections allows the contact calculation to be performed only on the sections that have contact detection points, which improves the speed of calculation.

#### 2.3.3 Contact force between a contact detection point and a contact surface

Figure 4 shows a contact detection point \( C \) on the vehicle coming into contact with a section of the contact surface on a railway structure. When the initial location of four points \( E_i \) \((i = 1-4)\) that determine the section on the global coordinate system is \( X_i \), the unit vectors \( (e_1 - e_3) \) that determine local coordinate system of the section can be expressed as (3).

\[
\begin{align*}
  e_1 &= (X_3 - X_1) / |X_3 - X_1| \\
  e_2 &= (X_1 - X_4) / |X_1 - X_4| \\
  e_3 &= e_1 \times e_2 / |e_1 \times e_2| \\
  e_4 &= e_3 \times e_1
\end{align*}
\]

(3)

With the solution at time \( t \) available, when the location of the contact detection point \( C \) at time \( t + \Delta t \) on the global coordinate system is \( X_{r,i} = (X^c_{r,i}, y^c_{r,i}, z^c_{r,i}) \), its location \( p^r \) on the local coordinate system of the section can be expressed as (4).

\[
\begin{align*}
  p^r &= \begin{pmatrix} p' \\ q' \\ r' \end{pmatrix} = \begin{pmatrix} (X^c_{r,i} - X_1) \cdot e_1 \\ (X^c_{r,i} - X_1) \cdot e_2 \\ (X^c_{r,i} - X_1) \cdot e_3 \end{pmatrix}
\end{align*}
\]

(4)

At time \( t + \Delta t \), with the contact detection point \( C \) at a distance of \( d_1 \) from \( E_1 \) on Line \( L_1 \), and \( E_3 \) at a distance of \( d \) from \( E_1 \), the normal coordinates \( \alpha \) of the contact detection point \( C \) toward Line \( L_1 \) on the contact surface can be ex-
pressed as (5).

\[ \alpha = \frac{d_i}{d} \quad (5) \]

When the displacement vector of \( E_i \) at time \( t + \Delta t \) is defined as \( \mathbf{u}_i + \Delta \mathbf{u} \) and the initial location of \( E_i \) at time \( t = 0 \) on the global coordinate system is defined as \( X_i \), the location \( X_i, \mathbf{u} \) of \( E_i \) at time \( t + \Delta t \) on the global coordinate system can be expressed as (6).

\[ X_{i,\mathbf{u}} = X_i + \mathbf{u}_{i,\mathbf{u}} \quad (6) \]

The location of points \( X_a \) and \( X_b \), which relate to the contact detection point \( C \), on Line L1 and L2 at time \( t + \Delta t \) on the global coordinate system can be expressed as (7) using the location \( X_{i,\mathbf{u}} \) of \( E_1, E_2, E_3 \) and \( E_4 \) at time \( t + \Delta t \) on the global coordinate system and the normal coordinate \( \alpha \).

\[ X_a = X_{1,\mathbf{u}} + \alpha (X_{4,\mathbf{u}} - X_{2,\mathbf{u}}) \]
\[ X_b = X_{1,\mathbf{u}} + \alpha (X_{4,\mathbf{u}} - X_{3,\mathbf{u}}) \quad (7) \]

When the locations of \( X_a \) and \( X_b \) on the local coordinate system of the contact surface are defined as \( P_a \) and \( P_b \), and their components are expressed as (8), the normal coordinate \( \beta \) of the contact detection point \( C \) in the direction perpendicular to L1 (\( e_3 \)) on the contact surface can be expressed as (9).

\[ P_a = \begin{bmatrix} p_a \\ q_a \\ r_a \end{bmatrix} \quad P_b = \begin{bmatrix} p_b \\ q_b \\ r_b \end{bmatrix} \quad (8) \]
\[ \beta = (q' - q_a)/(q_a - q_b) \quad (9) \]

When \( 0 \leq \beta \leq 1 \), the contact detection point \( C \) is between Line L1 and L2, i.e., within the section. The coordinate of the contact detection point \( C \) in the direction \( e_3 \) on the contact surface at the normal coordinate \( (\alpha, \beta) \) can be expressed as (10) by interpolating \( \beta \).

\[ r = r_a + \beta (r_b - r_a) \quad (10) \]

Therefore, the relative displacement (contact displacement) \( \delta_n \) between the contact detection point \( C \) and the contact surface can be expressed as (11).

\[ \delta_n = r - r' + \varepsilon(X_{i,\mathbf{u}}) \quad (11) \]

where, \( \varepsilon(X_{i,\mathbf{u}}) \) is irregularity preset on the contact surface. Contact force \( F_n \) is calculated assuming that the contact detection point \( C \) and the contact surface are not in contact with each other when \( \delta_n < 0 \) and that they are in contact with each other when \( \delta_n \geq 0 \). Contact force \( F_n \) can be expressed as (12) as a function of the relative displacement \( \delta_n \) between the contact detection point \( C \) and the contact surface.

\[ F_n = K_n(\delta_n) \quad (12) \]

where, \( K_n \) is the relationship between the relative displacement \( \delta_n \) and the contact force \( F_n \). \( K_n \) represents nonlinear characteristic such as elastoplastic deformation and local buckling between contact members, which are obtained from static loading tests or detailed FEM analyses.

Contact force \( F_n \) obtained by (12) is converted to a force and moments acting on the carbody’s center of gravity, which is then added to (1) for vehicle motion. Regarding the railway structures, contact force \( F_n \) is distributed to FEM nodes near the locations of contact and added as the node force to (2).

### 2.3.4 Contact forces between contact detection points and contact surfaces

This study also has to express phenomena such as wheelset members coming into contact with the side surface of the rail and wheel climb onto and over the top of a rail. To be able to simulate these phenomena effectively, rails need to be modeled with more than one contact surface. In addition, an algorithm for contact between a contact detection point and a number of contact surfaces needs to be developed.

Figure 5 shows a model of the contact surfaces of a rail. In this study, the rail consists of three contact surfaces. Figure 6 shows determination of contact or non-contact between the contact detection point and contact surfaces. To determine contact or non-contact, three contact statuses were defined. In Fig. 6, \( CS_{i,j} \) \((i = 1, \ldots, n; j: \text{the number of contact surfaces}) \) indicates the status of contact at time \( t \) between the contact detection point and the contact surface \( \Gamma_j \). \( CS_{i,1} = 1 \) indicates that the contact detection point and the contact surface are in contact with each other. \( CS_{i,1} = -1 \) indicates that they are not. \( CS_{i,0} = 0 \) also indicates a state of non-contact but implies initial penetration or entry into the contact range from the non-contact range of the contact surfaces.
2.4 Dynamic model for contact between wheels and rails

This study used conventional dynamic models for wheel/rail contact. A contact model taking into account the precise geometric forms of wheels and rails was used for the phases leading up to vehicle derailment. For the post-derailment phases, a simplified contact model of wheels in truncated shapes and rails with rectangular cross sections was used. Details can be found in the relevant thesis [4].

2.5 Numerical analysis method

DIASTARS III solves a system of equations of motion for vehicles and railway structures, thereby performing dynamic coupled analysis of multiple vehicles and railway structures. For efficient numerical analysis, DIASTARS III puts the equations of motion for vehicles and railway structures through modal transformation. The equations of motion for vehicles and railway structures on a model coordinate system obtained through this process are solved for each time increment $\Delta t$ using Newmark’s constant average acceleration method. As these equations of motion are nonlinear, calculation is repeated within $\Delta t$ until the unbalanced force is sufficiently small.

2.6 Validity of the analysis method

It is difficult to examine the validity of the analysis method in which the proposed contact models are incorporated through experiments using full-scale models. Experiments using reduced-scale models pose difficulties in reproducing constitutive laws related to areas that come into contact with each other, and therefore the experiments can only verify the behavior of multi-body model. The proposed analysis method should be considered valid based on the following premises:

1) Nonlinear behavior of vehicles leading up to derailment has been verified by full-scale model experiment [3] and mechanism analysis program [8].
2) The results of full-scale model experiments and detailed FEM are used for the contact springs between wheelset members and railway structures.

3. Practicality of the analysis method

This section discusses the trial calculations of post-derailment contact between wheelset members and track members that were performed using the analysis method described in Chapter 2. Specifically, trial calculations were made for contact between gear boxes and rails to verify whether the method could simulate the contact as well as the gear boxes rising above the top surface of the rails.

3.1 Analysis method

Figure 9 shows the analytical model for railway structures. Rails are considered as the running line of the wheels before derailment and are modeled by two long and suitably rigid beam elements. At each end of the rail, a large mass, of approximately $10^5$ times that of a vehicle, is...
placed for acceleration input, such as an earthquake. Rigid beam elements are added to define and model the 3 contact surfaces of the rail: one on top, and one on each side of the rail. This modeling is used for both the right-hand and left-hand rails.

Figure 10 shows the locations of the contact detection points on the wheelset members. The detection points were set to where contact with the rails was expected. Specifically, on the bottom of each of the four wheelset members arranged in a staggered pattern on the corresponding four wheelsets as shown in Fig. 10 (a), six contact detection points were arranged at 30 mm intervals horizontally perpendicular to the longitudinal direction of the rails as shown in Fig. 10 (b). The initial distance between the wheel and the wheelset members was set to 200 mm. The wheelset members were assumed to have a height of 300 mm. The contact springs between the gear cases and the rails were modeled as a linear spring with a spring constant of 30 kN/mm, which is equal to that of rail tilting springs.

As for input into the large mass, a single sine wave with a vibration frequency of 0.5-2.0 Hz and buffered at both the start and end was used. The waves were input in the same phase and horizontally perpendicular to the longitudinal direction of the rails. A single-car train was used and the running speed was set to 270 km/h.

3.2 Analysis results

Figures 11 and 12 show examples of the time-series wave forms. Figure 11 shows examples of cases conducted using a vibration frequency of 0.5 Hz and a vibration amplitude of 0.56 m where the wheelset members contact the side surface of the rails after derailment. Figure 11 (a) shows that the left and right wheels lift alternately because of the vibration, and then derail at about 4.5 seconds before falling on the track. Figure 11 (b) shows that the wheelset member comes into contact with the rail at about 4.7 seconds and then the right wheel touches the rail at about 5.8 seconds, thereby limiting the horizontal displacement of the wheelsets. This indicates that the rail becomes trapped in the gap between the wheelset member and rail.
and the wheel, which works as a vehicle guide device. Figure 11 (c) shows the time-series wave forms of the contact force between the wheelset member and the rail, which peaks at a significant level of about 480 kN. The peak force should be handled only as an example as the peak value is presumed to be heavily dependent on vehicle derailment mode, contact spring characteristics and distribution of contact detection points etc. The above shows that the proposed method is capable of simulating contact phenomena between wheelset members and trackside structures (rails).

Figure 12 shows examples of cases conducted using a vibration frequency of 1.0 Hz and a vibration amplitude of 0.2 m where the wheelset members come into contact with the top surface of the rail and then go beyond the rail after derailment. Figure 13 shows conceptual schematics of wheelset behavior. As shown in Fig. 12 (a), derailment occurs at about 2.5 seconds and the wheelset members come into contact with the top surface of the rail at about 2.7 seconds. When that occurs, a vertical contact force of about 210 kN is generated as shown in Fig. 12 (c). Subsequently, as the wheelsets go beyond the rail, their horizontal displacement increases as shown in Fig 12 (b). Then, at about 3.2 seconds, the members of wheelsets No.1 and No.3 come into contact with the side surface of the rail, and horizontal displacement is restrained, as shown in Fig. 13 (c). At about 5.4 seconds, wheelsets No2 and No.4 come into contact with the side surface of the rail, again preventing further horizontal displacement.

As demonstrated above, the proposed method is capable of simulating complex contact phenomena between wheelset members and track structures, such as wheelset members coming into contact with the top surface of the rail, going beyond the rail and coming into contact again with the side surface of the rail.

**Fig. 13 Conceptual schematics of wheelset behavior**

4. Conclusion

This study proposed a contact model capable of efficiently simulating contact between wheelset members and track structures, and conducted trial calculations using the proposed analysis method. This study can be summarized as follows:

1. A method was proposed for performing penalty-based calculations of dynamic contact forces working between contact detection points arranged on a multi-body vehicle model and contact surfaces defined in a FEM model of railway structures. A contact algorithm was developed capable of determining the contact status between contact detection points and a number of contact surfaces.

2. An analysis tool capable of simulating vehicle behavior taking into account contact between wheelset members and railway structures was developed by incorporating the above-described contact algorithm into an analysis program for dynamic interaction between vehicles and railway structures.

3. Trial calculations to investigate contact between gear boxes, representing wheelset members, and rails, representing track structures, showed that the proposed analysis method was capable of simulating wheelset members coming into contact with the rail, climbing onto the top surface of the rail and going beyond the rail.

References


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