Improvement of Dynamic Performance of Trucks with Longitudinally Unsymmetric Structures by Semi-Active Control for Rail Vehicles*

Yoshihiro SUDA** and Ronald J. ANDERSON***

This paper presents dynamic characteristics of unsymmetric suspension trucks with semi-active control to achieve compatibility between high-speed stability and curving performance. According to the direction of vehicle motion, the damping coefficient is switched so that the interwheelset structure, characterized by stiffness and damping, is asymmetric fore-and-aft. It was found in a previous study using a simple calculation model that curving performance is especially enhanced in comparison with conventional symmetric trucks. In this paper, unsteady state curving behavior of the proposed unsymmetric trucks during curve entry is calculated using full car body models with nonlinear wheel profile, considering nonlinear characteristics of the contact force between wheel and rail. Calculation results were compared with those for a conventional symmetric truck. The unsymmetric suspension truck with conical wheel profile has the best curving performance while keeping adequate stability even in sharp curves. The profiled wheel tread has not only superior steering ability but also a possibility to improve high-speed stability.

Key Words: Railway Vehicle, Truck, Semi-Active Control, Hunting Stability, Curving Performance

1. Introduction

The achievement of compatibility between high-speed stability and curving performance is vital for modern railways. A longitudinally unsymmetric truck with semiactive control has been proposed to achieve this purpose (1)-(4). According to the direction of vehicle motion, the interwheelset structure, characterized by stiffness, damping and linkage mechanism, switches in an asymmetric manner fore-and-aft. The controlled trucks of this concept are expected to exhibit excellent dynamic performance. Not only high-speed stability but also steering ability is improved because the opportunity to choose truck parameters is doubled. Curving performance is especially enhanced in comparison with conventional symmetric trucks. That is, the perfect steering condition is achieved in theoretical calculations so that the axles steer to radial positions. It was found in previous studies(4) that the attack angles of both the wheelsets become zero in curving simulations made using full car body models. To confirm the applicability of the proposed concept to real trucks, the effects of non-linear characteristics of the contact force between wheel and rail, centrifugal forces due to cant deficiency and secondary suspensions were examined. The results showed that these factors have an insignificant effect on the steering abilities. The next step which has not been previously examined is the influence of the wheel profile. The steering ability depends on the longitudinal creep forces between wheel and rail. The unsymmetric characteristics to satisfy superior performance also depend on equivalent conicity of wheel tread. It is important to examine the effects of arc profiled wheels not conical wheels on the dynamic behavior of the truck because it is likely that wheel profile is changed by tread wear although this type of truck is expected to have less opportunity of tread wear than conventional trucks due to the improved curving ability. Moreover there is a possibility that a well-designed wheel profile improves dynamic characteristics as usual in conventional trucks. In this paper,
unsteady state curving behavior of the proposed unsymmetric trucks during curve entry is examined by numerical simulations using full car body models with a nonlinear wheel profile. The hunting stability of vehicles is also examined by eigenvalue analysis, calculating the critical speed where the lateral motion of trucks becomes unstable and percent damping of truck hunting mode at given speed. The A'Gem Rail Vehicle Dynamics Software Package is used in calculations.

2. Basic Concept of Unsymmetric Truck with Semi-Active Control

Historically most railway vehicles have been designed to have longitudinal symmetry for bidirectional operation. Through the use of a switching device aided by semi-active control technology such as a damper with variable damping coefficient, the unsymmetric option becomes realistic. In previous studies the approach to make the truck structure longitudinally asymmetric in the traveling direction focuses on interwheelset structure and the unsymmetric arrangement of independently rotating wheels. Three configurations were considered: (1) unsymmetric suspension truck: the interwheelset structures such as suspension and linkage mechanism are unsymmetric, (2) unsymmetric wheelset truck: interwheelset structures remain symmetric but independently rotating wheels are used only on the trailing axle, (3) unsymmetric wheelset-suspension truck: both unsymmetric features are considered, i.e., unsymmetric interwheelset structure with a trailing axle of independently rotating wheels. The results are summarized as follows: the unsymmetric wheelset-suspension truck has the possibility of obtaining the highest critical speed among the three asymmetric trucks but this truck does not enable the condition of no-attack angle, i.e., perfect steering. On the contrary, the unsymmetric suspension truck has excellent curving performance such that the attack angle in both axles is zero in steady-state curving without cant deficiency. Decreased stability potentially exists but is improved by primary longitudinal dampers equipped in the leading axle. So, of the three configurations, only the unsymmetric suspension truck is considered here.

The basic concept of the proposed unsymmetric suspension truck is characterized by a truck with soft support of the leading axle which is longitudinally damped. The trailing wheelset has a hard longitudinal spring as is found in conventional trucks. In Fig. 1, an equivalent model of this unsymmetric suspension truck is shown. The asymmetry of this truck is represented as the difference of primary stiffness between the leading and the trailing wheelsets. The only unsymmetric stiffness is in the longitudinal direction. The unsymmetric stiffness index as was introduced and defined as the distance between the truck centerline and the support point of the shear stiffness when the interwheelset elastic structure is represented by the equivalent bending stiffness and shear stiffness. These values are expressed as follows:

$$a_s = -a \frac{k_{x1} - k_{x2}}{k_{x1} + k_{x2}}$$  \hspace{1cm} (1)

The condition for perfect steering ability, i.e., attack angle of zero, is represented by Eq. (2) under the assumption of linear creep force law without cant deficiency. Fortunately, the optimal value of unsymmetric suspension index does not depend on curve radius. However, it depends on the properties of wheel-rail contact such as longitudinal creep coefficient and equivalent conicity of the wheel.

$$a_s = \frac{k_{x2}b^2y}{2abf_{14}a + k_{x2}b^2y}$$  \hspace{1cm} (2)

The reason why a primary anti-yaw damper is used on only the leading wheelset is explained as follows: the soft support of the leading wheelset introduces wheelset oscillations so that the stability is low. Moreover, in order to improve the stability suited for high-speed trains, the following modification is considered: in the leading wheelset, the longitudinal primary dampers which act as yaw relaxation dampers are connected with hard longitudinal springs in series as shown Fig. 2. The combination of the damper and hard stiffness in series on the leading axle gives excellent performance: for truck hunting of high-frequency motions, the constraint becomes large, whereas for steering around a curve, which is a low-frequency motion, the constraint keeps the soft spring to achieve good steering ability.

The use of a primary yaw damper acting on the

![Fig. 1 Basic concept of unsymmetric suspension trucks](image-url)
leading wheelset introduces another merit to the unsymmetric trucks, i.e., it switches the primary longitudinal stiffness by changing the damping coefficient of primary longitudinal dampers which are installed in both sides between the axle box and truck frame in series with a hard longitudinal stiffness which is suitable for the trailing axle as shown in Fig. 2. That is, it gives the principle of the semi-active control. The soft longitudinal stiffness for the leading axle is set in parallel with these combinations of switched damper and stiffness. When the vehicle travels in one direction, the damper of the trailing axle box becomes stiff, i.e., damping action is almost lost and the damping coefficient becomes infinite. On the contrary, the damping characteristics of the leading axle are maintained at appropriate values to obtain adequate stability. The leading stiffness remains soft but the trailing one becomes hard. By the use of the switching device, the demand of bidirectional operation is satisfied.

![Fig. 2 Equivalent model of proposed unsymmetric suspension truck modified for bidirectional operation using series connection of switched primary longitudinal damper and stiffness](image)

3. Models and Method of Solution

3.1 Vehicle models and calculation method

The components such as stiffness and damping are assumed to have linear characteristics. The values of vehicle parameters used in this calculation are shown in Table 1 and are considered to fit high-speed trains of the standard gage. The wheel diameter, truck wheelbase and distance between trucks are reduced to achieve good stability by decreasing the weight. The equivalent wheel conicity is chosen as 0.15 to obtain suitable stability and curving performance. The maximum operating speed is assumed to be 200 km/h (55.5 m/s).

The A'GEM Rail Vehicle Dynamics Software Package\textsuperscript{5} is used in calculations of both the stability and curving performance. Kalmer's linear creep force law is used for stability calculations and determination of the unsymmetric index. The stability is analyzed by an eigenvalue routine. The indices of the stability are used as a critical speed at which the motions of trucks become unstable and the percent damping of truck hunting mode at the maximum operating speed of 55.5 m/s. For the predictions of curving performance, numerical simulations of curve entry were made. The FASTSIM routine\textsuperscript{6} is used for creep force calculations. In the model of conventional trucks, the degrees of freedom of the motion are 17, considering lateral and yaw motion about four wheelsets, two truck frames and one car body, and rolling motion of the truck frames and car body. In the model of the unsymmetric suspension truck, two additional motions of components are considered: two yawing motions of equivalent primary yaw damper of the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Values of vehicle parameter used in calculations</th>
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<tbody>
<tr>
<td><strong>Mass of wheelset</strong></td>
<td>500kg</td>
</tr>
<tr>
<td><strong>Yaw conicity of wheelset</strong></td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Wheel diameter 2r</strong></td>
<td>0.75mm</td>
</tr>
<tr>
<td><strong>Mass of truck frame</strong></td>
<td>1000kg</td>
</tr>
<tr>
<td><strong>Truck frame yaw and roll inertia</strong></td>
<td>400kgm(^2)</td>
</tr>
<tr>
<td><strong>Half spacing of primary suspensions</strong></td>
<td>0.9m</td>
</tr>
<tr>
<td><strong>Distance between two trucks</strong></td>
<td>16.0m</td>
</tr>
<tr>
<td><strong>Yaw inertia of primary yaw damper</strong></td>
<td>10kgm(^2)</td>
</tr>
<tr>
<td><strong>Height of center of gravity</strong></td>
<td>0.5m</td>
</tr>
<tr>
<td><strong>Distance between secondary suspension and car body centroid</strong></td>
<td>0.75m</td>
</tr>
<tr>
<td><strong>Wheelbase 2a</strong></td>
<td>2.5m</td>
</tr>
<tr>
<td><strong>Mass of car body</strong></td>
<td>3.0x10(^{9})kg</td>
</tr>
<tr>
<td><strong>Car body roll inertia</strong></td>
<td>1.0x10(^{9})kgm(^2)</td>
</tr>
<tr>
<td><strong>Car body yaw inertia</strong></td>
<td>1.5x10(^{9})kgm(^2)</td>
</tr>
<tr>
<td><strong>Track gage</strong></td>
<td>1.435m</td>
</tr>
</tbody>
</table>
leading wheelsets. Therefore, the degrees of freedom of the motion are 19.

3.2 Wheel profile used in curving simulations

Two types of wheel profiles are used in curving calculations. One is the almost conical profile with conicity of 0.15. This profile is modified from the standard conical profile of the former Japanese National Railways which has 1/20 conicity. From the viewpoint of curving ability of the proposed unsymmetric suspension trucks, constant conicity is desirable during lateral displacement of wheel as given in Eq. (3) which shows perfect steering condition. Another profile is similar to the arc tread profile of Japanese conventional trains. The conicity of conical part and curve radii of arc parts are modified to have equivalent conicity of 0.15 on the average. In Fig. 3, the normalized differences in rolling radii and the difference in contact angle versus lateral displacements of wheel are shown for both profiles. The profile of the rail used here is a Japanese standard (50 N Rail).

3.3 Setting of calculation conditions

If the unsymmetric suspension index satisfies the condition presented in Eq. (2), then perfect steering ability has been already achieved in previous studies. However, careful selection of the stiffness value should be conducted taking into account the stability. For unsymmetric suspension trucks with semi-active control, the value of the stiffness is determined to obtain maximum damping of truck hunting mode at 55.5 m/s. In this case, the damping is 28.3% and the critical speed is 194 m/s, while in the case of conventional trucks, critical speed is 271 m/s and damping is 30.0%. It is desirable that both conventional and unsymmetric suspension trucks have the same stability for comparison of curving performance, but it is impossible to select stiffness parameters which exactly agree with each other. In this calculation, the damping ratio is almost the same. The conventional truck has higher critical speed than the unsymmetric truck because the bending stiffness of the former is also higher as shown in Table 2, which plays an important role in relation to stability.

For the calculation conditions in curving, two curve radii and speeds are set. One is a 3,000 m curve radius where the vehicles are assumed to operate at the maximum speed of 55.5 m/s. Another is a 600 m curve radius at 27.7 m/s. Tight curves like these cannot be eliminated near stations and flange and rail wear is observed in even high-speed systems of Japan, leading to severe maintenance problems. Thus, the avoidance of flange contact and elimination of attack angles between wheel and rail in the negotiation of tight curves are significant for economical operations.

<table>
<thead>
<tr>
<th></th>
<th>Primary longitudinal stiffness of leading wheelset $k_{x1}$</th>
<th>Primary longitudinal stiffness of trailing wheelset $k_{x2}$</th>
<th>Primary lateral stiffness $k_{y}$</th>
<th>Unsymmetric suspension index $\alpha_2$</th>
<th>Equivalent bending stiffness $\alpha_2$</th>
<th>Critical Speed</th>
<th>Lowest damping at 55.5 m/s in truck hunting mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Truck</td>
<td>$5.00 \times 10^6$ N/m</td>
<td>$5.00 \times 10^6$ N/m</td>
<td>$5.00 \times 10^6$ N/m</td>
<td>0.0 m</td>
<td>8.10 $\times 10^6$ N/m</td>
<td>271 m/s</td>
<td>30.0%</td>
</tr>
<tr>
<td>Unsymmetric suspension truck</td>
<td>$1.45 \times 10^6$ N/m</td>
<td>$1.26 \times 10^7$ N/m</td>
<td>$1.26 \times 10^6$ N/m</td>
<td>0.99 m</td>
<td>4.21 $\times 10^6$ N/m</td>
<td>194 m/s</td>
<td>28.3%</td>
</tr>
</tbody>
</table>

Fig. 3 Properties of wheel-rail contact used in calculations

In both conditions, the vehicle speed is set to eliminate the effect of centrifugal force which is balanced with a cant.

4. Results of Calculations

4.1 Curving performance with conical wheel profile

At first, results of curving simulations of the proposed unsymmetric suspension truck are compared with those of conventional symmetric truck in the case of almost conical profile. Figure 4 shows the simulation results for 3000 m curve radius. The vehicle travels at 55.5 m/s without centrifugal force. The length of clothoid spiral is 80 m, beginning at 1 m and ending at 81 m. Only the result of the leading wheelset of the leading truck was displayed because this axle had the worst curving ability among the four wheelsets. In a large curve radius condition, there is little difference between the conventional truck and the unsymmetric suspension truck. Both trucks can negotiate with low attack angles, avoiding flange contact. If the curve radius is large, high steering ability is not required although both attack angles and lateral displacement of the conventional truck become larger.

The small curve radius of 600 m, however, makes the deficiency of the curving ability of the conventional truck clear as shown in Fig. 5. The vehicle speed is 27.7 m/s and the length of transition curve is 80 m which is the same as the case of 3000 m curve radius. In the conventional truck, the flange contact can no longer be avoided in the leading wheelset of the leading truck. The attack angles of the conventional truck, which are an index of lateral force between wheel and rail, become very large and lead to wheel/rail wear. On the contrary, the proposed truck, i.e., the unsymmetric suspension truck, can negotiate not only without flange contact but also with almost perfect steering actions. The off-flange ability and small

Fig. 4 Results of curving simulations
(Behavior of the leading wheelset of the leading track in 3000 m curve radius at speed of 55.5 m/s)

Fig. 5 Results of curving simulations
(Behavior of the leading wheelset of the leading truck in 600 m curve radius at speed of 27.7 m/s)
attack angles are beneficial to eliminate wear of both wheels and rails.

These results show that the excellent steering ability is maintained even with nonlinear wheel profile although the unsymmetric index is determined by the linear calculations. The reason why nearly perfect steering is achieved in the unsymmetric suspension truck is that the moment acting on a wheelset can be cancelled by the longitudinal creep force between wheels and the rail. The unsymmetric support of the wheelset induces the natural tendency to follow ideally the given track alignment. The detailed mechanism is discussed in a previous paper\(^{10}\).

4.2 Curving performance with arc wheel profile

The results with arc profiled wheel are plotted on the thin lines as shown in Figs. 4 and 5 for 3 000 m and 600 m curve radii, respectively. The curving behavior of 3 000 m curve radius is almost the same as trucks with conical wheels. If the curve radius decreases, the difference between arc profiled wheel and conical profile becomes clear. In the conventional truck, the attack angle of the leading wheelset is somewhat improved by the use of arc profile but flange contact still occurs. The attack angles of the proposed unsymmetric suspension truck become somewhat worse by the use of the arc profiled wheel. However, both values are still quite small and almost the same as those of the conventional truck in 3 000 m curve radius.

The reason why the steering ability decreases with the use of a worn wheel is explained as follows: in this calculation, the unsymmetric index is chosen using linear creep coefficient and equivalent conicity of 0.15. The equivalent conicity of the profiled wheel used here varies from 0.1 to 0.2 depending on the lateral displacement of the wheel. Thus, there is a difference between the value of the equivalent conicity for truck design and the actual value. Moreover, even if the equivalent conicity is almost the same as 0.15 at the lateral position of leading wheelsets during curving, the perfect steering ability depends on not only equivalent conicity but also wheel lateral position. The lateral displacements of the arc profiled wheel of both leading wheelsets are larger than those of conical profile as shown in Fig. 5. Consequently this curving condition cannot exactly satisfy perfect steering criterion.

4.3 Improvement of stability with arc wheel profile

The arc profiled wheel does not contribute to improvement of steering ability in the proposed unsymmetric suspension truck with semi-active control. However, the use of an arc profiled wheel has the possibility to compensate for this demerit, that is, to improve high-speed stability. If the index is selected to obtain excellent steering performance, the unsymmetric suspension truck has potentially low stability, although stability itself is enhanced by adopting another asymmetric index. On a straight track at high-speed operations, the lateral displacements of the wheelsets are small, while wheelsets have large displacements in small curve radius at moderate speed. Then it is expected that the equivalent conicity decreases when vehicles travel at high speed.

Figure 6 shows the effect of equivalent conicity on the stability of the proposed unsymmetric truck when the unsymmetric index is kept at the condition that conicity is 0.15. The critical speed increases if actual wheel conicity decreases. Thus, this method is one option to obtain high-speed stability for the proposed trucks.

5. Conclusions

The dynamic characteristics of the proposed unsymmetric suspension trucks with nonlinear wheel profile have been examined using the AGEM Rail Vehicle Dynamics Software Package. The proposed truck has the feature that the primary longitudinal stiffness of the trailing axle is larger than that of the leading axle and the primary yaw damper is set only on the leading axle. A switched damper with variable damping coefficient aided by semi-active control technology solves the demand of bidirectional operation. The following results are obtained: the attack angle nearly equals zero during curve negotiation through the transition curve and no flange contact is observed even in curves of 600 m radius, though conventional trucks of the size considered here cannot negotiate without flange contact and large attack angle. The conical profile has better steering ability rather than arc profiled wheel because perfect steering ability requires constant equivalent conicity for lateral displacement of the wheelset. However, decreased conicity of the arc profiled wheel during small fluctuations of the wheel leads to a higher critical speed. Applicability of the proposed unsymmetric suspension trucks is verified from calculation results obtained.
References


