Study on How Wheel Flat Shapes Affect Axle Box Acceleration

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It is very important to evaluate the effect of wheel flats on the acceleration of axle boxes. To understand the mechanism of the collision of the rotating wheel with a roller rig after losing contact with the roller rig, firstly, we conducted bench tests using a roller rig with a bogie set which had a wheel flat. A dynamic simulation model was then built and verified by comparing simulation and experimental results. This paper reports on how the shape at the edge of the wheel flat affects the vertical acceleration of axle boxes.

Key words: wheel flat, vertical acceleration of axle boxes, bench tests, roller rig, collision, simulation model

1. Introduction

A wheel flat is generated on a wheel tread when the braking force exceeds the frictional force on a rail and the wheel locks and slides on the rail. The wheel flat then generates impulsive forces on both the railway vehicle itself and the tracks. This can cause vibrations which do not occur with regular train operation and can cause bogie parts to be damaged and fall off. In Japan, running tests were carried out to investigate the basis for the maximum admissible length of 75 mm for a wheel flat, which was based on feedback collected from previous incidents. In the tests in 1960s, experimental results showed that the ratio of impact pressure on a rail to the length of the wheel flat increased rapidly when it reached 75 mm, although vertical acceleration of ballast stayed almost flat. From these experimental results, these criteria have been applied by railway companies in Japan since then.

However, when a train is in operation the shape of the wheel flat is modified by grinding work on site by comparing the length of the wheel flat with the permissible length. This paper reports on the experimental results obtained from bench tests using a bogie with a wheel flat on the wheel tread to understand wheel/rail contact conditions and the collision mechanism between them. Then, a dynamic vehicle model consisting of a half carbody with a modified wheel flat and rounded with an R-shaped edge was built and verified through experimental results obtained in bench tests. Finally, we discuss how the different patterns of the round shaped edge affect the wheel/rail contact conditions by varying collision velocities and contact duration of the wheel with the roller.

2. Bench tests using a roller rig

2.1 Configurations of roller rig and test bogie

A wheel with a wheel flat machined on the tread was installed on a test bogie. Figure 1 shows the wheelset with the wheel flat set on the roller rig. Dead weights on a loading cage were vertically

loaded on the bogie to duplicate a load nearly equal to half the weight of an empty carbody. The loading cage had three degrees of freedom; vertical, pitching, and yawing direction neither longitudinal, lateral nor rolling direction in structure.

The wheelset opposite to the tested wheelset was set on the ground and longitudinally immobilized and fixed it in position using wedges. Strain-gauge type accelerometers were affixed to both axle boxes to measure vertical acceleration. The wheelset was driven by a rotating roller up to a speed of 130 km/h, equal to the maximum running speed found on some conventional lines in Japan. At each constant speed, the acceleration was measured for approximately one minute.

Fig. 1 Bogie set on roller rig

2.2 Tested wheel with wheel flat

A brand-new wheel with a diameter of 860 mm was used for testing. The length of the wheel flat was equal to the maximum admissible length of 75 mm. Figure 2 shows the dimension of the wheel flat. Figure 3 shows the photo of the wheel flat machined on the tread and the ground edge, located between the tread and the wheel flat, which was modified and rounded with a grinder.

Fig. 2 Dimensions of artificial wheel flat

Fig. 3 Photo showing 75 mm-long artificial wheel flat with ground edges

2.3 Experimental results obtained in bench tests

Figures 4a and 4b show waveforms of vertical acceleration of the axle box on one side of the wheels with the wheel flat comparing the experimental results obtained before and after shape modification, measured at the speed of 30 km/h and 80 km/h. At a speed of 30 km/h, the acceleration denoted by arrows with (A) decreased due to the shape modification shown in Fig. 4a. After the wheel began jumping, the positive acceleration denoted in (B) diminished with the shape modification of the edge of the wheel flat at the moment of colliding with the roller again. Meanwhile, at a speed of 80 km/h, the shape modification caused the acceleration (A) caused by colliding with the roller double, by comparison to the case where the shape was not modified. The positive acceleration (B) generated by secondary collision with the roller appeared only for the wheel with the shape modification, not for the wheel without the shape modification. This was because the secondary collision of the wheel without the shape modification with the roller coincided with a shallow spot on the wheel flat.

Then, in order to focus on the acceleration (A) due to the first collision with the roller, Fig. 5 shows the maximum values of the amplitude of the acceleration with respect to different running speeds. The maximum value of the vertical acceleration of the axle box close to the wheel flat without the shape modification peaked at 35 km/h. In the case of the wheel with the shape modification, the maximum value was smaller than the wheel without the modification at a lower speed of 50 km/h, whereas it increased with higher speeds from 50 km/h to 80 km/h. Then, the maximum value of the vertical acceleration of the axle box rose by 1.5 times above that of the wheel flat without the shape modification. The maximum values of the acceleration specifically increased at speeds of 110 km/h and 120 km/h, because sympathetic vibration appeared in the test set and affected the vertical acceleration of the axle box. From these experimental results, we confirm that there is a clear difference in the peak value and the speed where the acceleration reaches the peak in accordance with the presence of the shape modification for the edge of the wheel flat. The mechanism for making the difference is dis-

(a) 30 km/h (Rotation Period : 0.32 s)

(b) 80 km/h (Rotation Period : 0.12 s)

Fig. 4 Evaluation of vertical acceleration affected by R-shaped edge at speeds of 30 km/h and 80 km/h

Fig. 5 Comparison of maximum vertical acceleration of axlebox to running speed

cussed using a dynamic model in the following section.

3. Experimental verification of dynamic simulation model

3.1 Configuration of dynamic simulation model

Figure 6 shows the dynamic simulation model for the vehicle set on the roller rig. The dynamic simulation model consists of a weight loading cage, a bogie frame, axle boxes, wheelsets and rollers, all of which are assumed as rigid bodies. These bodies are mutually connected and supported with springs and damping elements. The axle box has a spring and a damper in it to reproduce equivalent bending stiffness of the wheelset [1, 2].

A motion equation is given by

$$M \frac{d^2 q}{dt^2} + C \frac{dq}{dt} + Kq = F \quad (1)$$

where M is a mass matrix of rigid bodies;
 C : damping matrix of damping components;
 K : stiffness matrix of springs;
 q : vector of generalized coordinates; and
 F : vector of external forces.

By numerically integrating the differential equations derived from in (1) with the Runge Kutta-Gill method, we obtain velocities and displacement as for 22 degrees of freedom of the dynamic simulation model.

3.2 Geometrical relationships between the shapes of wheel flat and roller while rotating

The modified shape of the edge of the wheel flat is modeled as arcs with curvature radii r_1 and r_2 inscribed in a circle with a curvature radius r_0 and touched with the wheel flat. A contact point between the wheel tread and the roller is determined by a longitudinal displacement of the center of the wheel and a wheel rotational angle. Therefore, the contact conditions between the wheel and the roller determined in geometric relationships is classified and defined as phase 0, phase 1, phase 2 and phase 3 to evaluate the descent displacement of the center of the wheel and interactive force between

the wheel and the roller. These phases are determined in accordance with the contact point on the wheel flat with the roller. In phase 0, the wheel contacts with the roller on normal part of the wheel tread. Phase 1 and phase 3 mean the periods in which the wheel is rotating and contacting with the roller at the front edge or the rear edge of the wheel flat. And phase 2 is defined as the period in which the flat plane on the wheel flat is contacting with the roller. Figure 7 describes geometric relationships between the centers of the wheel with the wheel flat and the roller. The origin of the rotational angle of the wheel θ_w is located where the front edge of the wheel flat coincides with the point right below the center of the wheel. Symbols shown in Fig. 7 are defined as follows:

r_0 : radius of the wheel;
 R_0 : radius of the roller;
 δ : angle subtended between a perpendicular and a line segment from the center of the roller to the contact point; and
 X_w : longitudinal displacement of the center of the wheel.

3.3 Vertical displacement of center of the wheel rotating on roller

Assuming that the wheel and the roller are rigid bodies, we can geometrically determine the vertical displacement of the center of the wheel with continuous mutual contact with the roller during rotating. Vertical relative displacement of the center of the wheel Δh is calculated by subtracting the initial height h_0 from the current height h . Vertical relative displacement Δh is derived as a function of θ_w and X_w .

3.4 Vertical displacement of center of the wheel rotating on roller

Both of wheels and rollers are made of steel, and the cross-section shapes at the mutual contact point are formed as arcs. When those objects contact each other, both of the contact point and nearby area can be locally assumed as an elastic body by Hertzian contact theory. Furthermore, from the results of the previous research that the theory of elasticity can explain the mechanism for collision and deformation in the case that two spheres mutually collide at a lower relative velocity than 1 m/s, vertical contact force $N_{(i)}$ is mod-

Fig. 6 Dynamic model of bogie set on roller rig

Fig. 7 Schema showing contact conditions and geometrical relationships between roller and wheel

eled as the force of a non-linear Hertzian spring, which generates the force obtained by the spring displacement $st_{(i)}$ to the power of 3/2 denoted in (2) [3]. The spring constant k_{rz} in (2) is calculated from static wheel load and static deformation of the wheel derived from Hertzian contact theory [4]. The spring displacement is obtained from (3).

$$N_{(i)} = -sgn(st_{(i)}) k_{rz} |st_{(i)}|^{3/2} \quad (2)$$

$$st_{(i)} = \{z_w \mp b_{(i)}\phi_w - (z_r \mp b_{(i)}\phi_r) - \Delta h_{(i)}\} \cos \delta_{(i)} \quad (3)$$

$(i = r, l)$

where z_w is the vertical displacement of the wheel;

ϕ_w : roll angle of the wheelset;

z_r : vertical displacement of the roller;

ϕ_r : roll angle of the roller; and

$b_{(i)}$: length between the center of the wheelset and the contact point.

A suffix 'i' is used to distinguish right and left wheels. The symbol of sgn in (2) means the sign of $st_{(i)}$. The determination of mutual contact condition of the wheel with the roller is based on whether the contact spring force is less than zero or not. If the wheel is determined to lose the contact with the roller, the $N_{(i)}$ is set to be zero. When $N_{(i)}$ is equal to zero, longitudinal creep force is not generated as well.

3.5 Influence evaluation on vertical acceleration of axle box

Figure 8 shows the results comparison of the dynamic simulation and the bench tests which consists of maximum values of the vertical acceleration of the axle box for each speed. The dynamic simulation model reproduces the trend curve of the vertical acceleration of the axle box close to the unmodified wheel flat which has the peak value at a speed of 35 km/h. With the modified wheel flat, the maximum value of the vertical acceleration of the axle box becomes lower than that of the unmodified wheel flat at a lower speed than 50 km/h. Furthermore, it is well simulated that the maximum vertical acceleration of the axle box with the modified wheel flat rises higher than that with the unmodified wheel flat at a higher speed than 50 km/h.

Fig. 8 Verification of numerical model comparing with experimental data

4. Collision and contact conditions of wheel with roller

4.1 Effect of the shape of edge on vertical acceleration of axle box

Figure 9 shows the simulation results of maximum values of the vertical acceleration of the axle box in the dynamic simulation model, where the inradii r_1 and r_2 of the edges of the wheel flat are changed to five radii of 1 mm, 100 mm, 200 mm, 300 mm, and 400 mm. The radius of the opposite edge of the wheel flat to the rounded edge is designed to 1 mm. When the inradius r_1 of the front edge was increased, it was observed that the maximum value of vertical acceleration tended to fall until the speed entered the range 25 km/h to 30 km/h, where the peak value for $r_1=1$ mm was obtained, as shown in Fig. 9a. However, as r_1 increased in length, the speed at which the value peaked shifted to a higher speed range. In the case of an edge with radius r_1 of 400 mm, the peak value increased 1.9 times at a speed of 80 km/h, above the peak value when r_1 was 1 mm. Meanwhile, the curvature radius r_2 was increased, the maximum values of the vertical acceleration of the axle box demonstrated a decreasing trend at a lower speed than 70 km/h. Peak values were obtained for $r_2=1$ mm, 100 mm, 200 mm and 300 mm at 25 km/h. When $r_2=400$ mm, no peak value was observed at any speed and the maximum

value of acceleration of the axle box showed a gradual downward trend at speeds in excess of 20 km/h.

(a) Rounded front edge

(b) Rounded rear edge

Fig. 9 Effect of edge radii on maximum values of vertical acceleration of axlebox

4.2 Effect of edge shape on collision velocity

When a wheel loses contact with the roller, the potential energy stored in the axle spring is transformed into downward kinematic energy of the wheel. Therefore, the longer the contactless rotation, the greater the kinematic energy translated from the potential energy. Figure 10 describes the vertical collision velocities of the wheel to the roller at any running speed obtained by the dynamic simulation. Negative velocity means downward motion. The data below 60 km/h in the case of $r_1=400$ mm, $r_2=1$ mm was eliminated from the evaluation, because they differed from the other cases of the combination of r_1 and r_2 , where the wheel jumped up after losing contact with the roller in the time defined as phase 3, and the normal part of the tread collided with the roller. As in the case of $r_1=1$ mm and $r_2=1$ mm in Fig. 10, the absolute value of the collision velocity peaked at 20 km/h and showed a downward trend up to 60 km/h. It stayed flat at running speeds over 60 km/h. When $r_1=1$ mm and $r_2=400$ mm, the absolute value of the collision velocity decreased in proportion to running speed. For $r_1=400$ mm and $r_2=1$ mm, the absolute value of the collision velocity peaked out at 80 km/h and showed a decreasing trend at speeds over 80 km/h.

4.3 Effect of edge shape on collision velocity

Figure 11 shows durations of contactless rotation of the wheel

Fig. 10 Effect of edge radii on vertical collision velocities of wheel

Fig. 11 Effect of edge radii on duration of contactless rotation of wheel

classified by the edge shape of the wheel flat with respect to the running speeds. For the reason mentioned in the previous section 4.2, the data obtained at speeds below 60 km/h, the cases where $r_1=400$ mm, $r_2=1$ mm were eliminated from the evaluation. As shown in Fig. 11, in the case of $r_1=1$ mm, $r_2=1$ mm the duration of contactless rotation reached a maximum at 25 km/h and became shorter at speeds over 25 km/h.

When $r_1=1$ mm, $r_2=400$ mm there was also a similar tendency for the duration of contactless rotation to decrease in accordance with the increase in running speed. By comparing the result obtained in the case of $r_1=1$ mm, $r_2=1$ mm with results obtained when $r_1=1$ mm, $r_2=400$ mm at the same running speeds, we noticed that the shape modification of the rear edge of the wheel flat made the duration of contactless rotation longer than the unmodified rear edge. This is because the collision spot was in the rear area of the rear rounded edge with the curvature radius of $r_2=400$ mm, according to the increase of the running speed. It follows that the length of the contactless rotation grew. Furthermore, when $r_1=400$ mm, $r_2=1$ mm, the duration of the contactless rotation peaked out at 80 km/h and became shorter at speeds over 80 km/h. We noticed that the expansion of the inradius r_1 to 400 mm resulted in shifting of the spot which lost contact with the roller rig, to move further away from the front edge of the wheel flat as the running speed reached 70 km/h.

5. Conclusions

We conducted bench tests with an actual bogie which had a wheel set with a wheel flat and installed on a roller rig, to evaluate the effect of the shape of the edge of a wheel flat on contact conditions and collision behavior of the wheel with the roller. Moreover, we built a dynamic simulation model composed of a weight loading cage, a bogie, two wheelsets and rollers set on the roller rig. The experimental and simulation results can be summarized as follows:

(1) From the experimental results of the maximum values of the vertical acceleration of the axle box obtained in bench tests conducted up to speeds of 130 km/h, we confirmed that the maximum values of the vertical acceleration of the axle box close to the wheel flat without the modified shape peaked at 35 km/h, and that of the axle box close to the wheel flat with the front edge rounded peaked out at approximately 80 km/h. The latter peak value rose by a factor of 1.9 compared with the former one. Although the maximum value of the vertical acceleration of the axle box was reduced with the shape modification of the front edge of the wheel flat at a lower speed than 50 km/h, we found that there was a tendency for it to increase at running speeds over 50 km/h up to the speed where it peaked out.

(2) We applied the two parameters of r_1 and r_2 , which are the inradii of the edges of the wheel flat, to dynamic simulation in five case studies to evaluate the effect of the parameters on the maximum value of the vertical acceleration of the axle box. In accordance with the increase of the inradius r_1 of the front edge of the wheel flat, the maximum value of the vertical acceleration of the axle box is reduced in a lower speed range. Furthermore, the running speed where its peak value is obtained shifts to a higher speed range due to the shape modification of the front edge, and the peak value exceeds the one obtained in the case of the wheel flat without shape modification. The expansion of the inradius r_1 to 400 mm resulted in longer

periods of loss of contact during rotation, which caused an increase in the wheel's downward collision velocity. Meanwhile, the expansion of the inradius r_2 did not cause a clear difference in the running speed where we found the peak value of the vertical acceleration of the axle box, when being compared with the case of $r_2=1$ mm. At speeds below the range where the peak values of the vertical acceleration were obtained, the maximum values of the vertical acceleration of the axle box close to the modified wheel flat, were below the maximum values obtained when $r_2=1$ mm. In the contrast, we found that there was a tendency for these values to increase in the higher speed ranges, compared to when $r_2=1$ mm. This is because the collision velocity with the roller rises as the period of rotation after loss of contact between the wheel and the roller, lengths.

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