RAIL CORRUGATION IN THE PROCESS OF BRAKING

Kargapoltsev, Sergey K. *– Irkutsk State University of Railway Engineering, Irkutsk, Russia.*
Novoseltsev, Petr V., *Irkutsk State University of Railway Engineering, Irkutsk, Russia.*
Kuptsov, Yuri A., *Irkutsk State University of Railway Engineering, Irkutsk, Russia.*

ABSTRACT

It was found in the course of the study that oscillations of the vehicle wheelset's angular velocity during braking should be recognized as the principal cause of rail corrugation. Over a single period, two alternating events occur: an elastic interaction between the wheel and the rail, and their slipping relative to each other causing friction and formation of a valley. The wavelength of corrugation wear increases with the increase of the train speed and the value of the braking torque. In order to reduce the intensity of wear, the track stiffness should be increased, the braking torque reduced, and the suspension's parameters optimized.

Keywords: railway, rail corrugation wear, wheelset, adhesion coefficient, braking torque, track longitudinal stiffness, angular velocity, wheel slip, friction.

Background. *According to statistical data, the rail traffic load (by the tonnage passed) borne by the rail over its service life varies from 100 million tons to 2.5 billion tons gross [1, 2]. The cause of such a wide variation (25 times the minimum) in the service lives of rails typically lies in the unsatisfactory dynamics of the 'vehicle – track' system [3].*

Our analysis demonstrates that the maximum values of the dynamic additions to the pressure of the wheel on the rail that arise during the movement of the rolling stock are 90 % attributable to the irregularities of the track [4–6]. Corrugation wear affects from 10 to 30 % of railway tracks. By shape, two characteristic types of wavelike wear are distinguished: short wavelength (0.03 to 0.08 meters) irregularities (corrugations) with light humps and dark valleys, and long wavelength (from 0.2 to 2 meters) irregularities (waves).

According to a number of authors [7, 8], the formation of wavelike wear irregularities of rails is initiated by or linked to the following factors:

– non-uniform distribution of metal hardness across the depth and along the length of the rail;

– residual stresses;

– irregularities formed on the head of the rail during rolling and cold straightening;

– emergent vertical shocks;

– wheel slips (especially on curved segments);

– non-uniform elasticity of the rail support system (the supporting structures under the rail).

Objective. *The factors listed above, however, fall short of answering the key questions:*

– why wavelike wear does not occur on all segments of the rail?

– why is it of a periodic nature?

– why are the wave lengths different in different segments?

– why does this type of wear occur not only in curves but also on straight runs of the track?

Let us make an attempt to answer these questions.

Methods. *The authors use mathematical methods, modeling, engineering methods.*

Results. *Let us review the process of a rail vehicle's service braking that is initiated by pressing a brake shoe against the wheel tread. The wheel continues to rotate but the friction gives rise to forces emerging in the interaction between the shoe and the wheel, and between the wheel and the rail.*

The wheel's angular velocity ω_0 is related to the linear velocity V of the wheel's hub that is equal to the speed of the vehicle:

$$\omega_0 = \frac{V}{R}, \qquad (1)$$

where R is the radius of the wheel (in meters).

During braking, the relation expressed by the equation (1) becomes impossible; the rotation of the wheel slows down at a greater rate than the vehicle does.

The process of interaction between the wheelset and the track during braking unfolds as follows (Pic. 1):

– the braking torque M reduces the angular velocity ω_0 of the wheelset;

– the wheel applies the adhesion force F' to the rail:

$$F' = Q \cdot \psi, \qquad (2)$$

where Q is the vertical load of the vehicle's weight applied to the wheel, and ψ is the adhesion coefficient;

– under the impact of the force F', deformation of the rail track occurs giving rise to an elastic force in the rail:

$$F'' = C_p \cdot S, \qquad (3)$$

where C_p is the longitudinal stiffness of the track (in N/m); S is the longitudinal deformation of the track (in meters);

and this elastic force is applied to the wheelset thanks to the adhesion between the wheels and the rails:

$$F'' = C_p \cdot \varphi_1 \cdot R, \qquad (4)$$

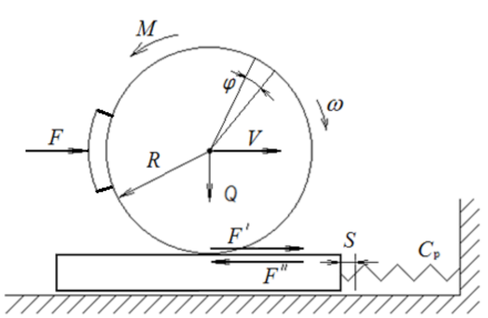
where φ_1 is the additional small angular shift during the oscillation of the wheelset;

– in the event that the elastic force is greater than the force of adhesion, wheel slip occurs; the rail will exert a sliding friction force on the wheelset:

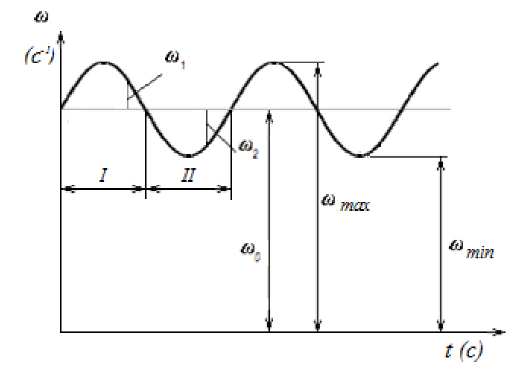
$$F = Q \cdot f, \qquad (5)$$

where f is the sliding friction force coefficient that is smaller than the coefficient of adhesion between the wheel and the rail: $f < \psi$.

As the adhesion fails and the sliding begins, the angular velocity $\omega = \omega_0 + \omega_2$ of the wheelset is reduced. During sliding, the longitudinal force exerted by the wheel decreases, and the energy of compression



Pic. 1. Analytical model of the wheelset braking process.



Pic. 2. Changes in the angular velocity of a wheelset during a steady braking mode.

accumulated in the rail causes the rail to move in the direction opposite to the direction of the sliding. As is known, in dry friction the friction coefficient decreases as the speed of sliding increases, which facilitates the sliding of the wheel on the rail. As the energy of deformation accumulated in the rail fades and the rail is moved back by the elastic force, the slip is reduced and the adhesion between the wheel and the rail is restored. The force exerted on the wheel by the rail increases while the angular velocity of the wheel set rotation decreases.

In the process, the wheel slips relative to the brake shoe at a speed that changes according to a periodic law. This oscillating system also has some stiffness.

As a result of such complicated interactions, oscillatory motions of the wheel and the rail emerge, with periodic slips.

Pic. 2 is a graph showing the change of the angular velocity of the wheelset's rotation during a certain small time interval, when the reduction of the angular velocity of the wheel's rotation is insignificant. Here, ω_1 is the change in the wheelset's angular velocity in the small oscillations mode during the elastic interaction with the rail; ω_2 is the change in the wheelset's angular velocity in the small oscillations mode during slipping.

In the small oscillations mode of the wheelset during braking, the rail track is an elastic link, i.e. the wheelset and the rail track make up an oscillatory system. The differential equation of this system in an elastic interaction is:

$$\frac{d^2\varphi_1}{dt^2} + K_1^2 \cdot \varphi_1 = \frac{M}{J}, \qquad (6)$$

where φ_1 is the angle of rotation of the wheelset at small oscillations during the period of elastic interaction; J is the wheelset's axial moment of inertia (kg • m²).

In this equation, K_1 is the «wheelset-rail track» system's intrinsic frequency of oscillations:

$$K_1^2 = \frac{C_p \cdot R^2}{J}. \qquad (7)$$

As can be seen from equation (7), K_1 is dependent on the rail track's longitudinal stiffness C_p; as the latter decreases, the intrinsic frequency K_1 also decreases. The value of C_p is reduced as the health of the rail track deteriorates.

Differential equation (6) has the following solution:

$$\varphi_1 = \frac{M}{J \cdot K_1^2} \cdot (1 - \cos K_1 \cdot t). \qquad (8)$$

Equation (6) is applicable as long as the force of adhesion between the wheel and the rail is greater than the elastic force of the rail track. This is expressed by the inequality:

$Q \cdot \psi \geq C_p \cdot \varphi_1 \cdot R.$ (9)

If the inequality is not met, adhesion is lost and wheel slipping occurs. From equation (9), we can derive the angle at which wheel slipping is probable:

$$\varphi_1 = \frac{Q \cdot \psi}{C_p \cdot R}. \qquad (10)$$

Plugging (9) into (8), we obtain the condition of equilibrium in the «wheel set-rail track» system:

$$\frac{Q \cdot \psi}{C_p \cdot R} = \frac{M}{J \cdot K_1^2}(1 - \cos K_1 t). \qquad (11)$$

The time t_1 at which loss of adhesion is likely equals:

$$t_1 = \frac{1}{K_1} \arccos\left(1 - \frac{Q \cdot \psi \cdot J \cdot K_1^2}{C_p \cdot R \cdot M}\right). \qquad (12)$$

Let us consider an example with the following givens:

Q = 22 • 10⁴ N; ψ = 0.3; J = 400 kg • m²; C_p = 125 ·10⁶ N/m; R = 0.5 m; M = 2.5 • 10⁴ N·m. The duration of the elastic interaction between the wheel set and the rail needs to be determined.

In step one, we compute the intrinsic frequency K_1 using formula (9):

$$K_1 = \sqrt{\frac{125 \cdot 10^6 \cdot 0.5^2}{400}} = 279 \sec^{-1}.$$

Then, the duration using formula (12):

t_1 = 0.00677 sec.

Over the period of t_1 = 0.00677 sec a point on the rim of the wheel will travel the following distance:

$\Delta S_1 = V \cdot t_1$,

where V is the speed of the train (in m/sec), ΔS_1 is that part of the rail track where its elastic interaction with the wheel set occurs and at the same time it is part of the wavelength of the wavelike wear.

In our example at V = 10 m/sec:

ΔS_1 = 10 • 0.00677 = 0.0677 m.

When the wheel set is moving in the small oscillations mode, at the moment in time t_1 the skid angular velocity of the wheel set is equal to:

$$\omega_1 = \dot{\varphi}_1 = \frac{M}{J \cdot K_1} \sin K_1 t_1.$$

In our example at t_1 = 0.00677 sec:

$$\omega_1 = \frac{2.5 \cdot 10^4}{400 \cdot 279} \sin(279 \cdot 0.00677) = 0{,}21 \sec^{-1}.$$

After the adhesion has been lost, the wheel set is under the impact of the braking torque M and the force of kinetic friction exerted by the rail. In this mode, the rail causes the rotation of the wheel in the direction of the train's movement (Pic. 3).

In Pic. 3, the kinetic friction force is:

T = Q • f, (13)

where f is the kinetic friction coefficient that is smaller than the adhesion coefficient;

V_p is the velocity of the rail's recoil motion.

The differential equation describing the motion of the wheel set in the sliding mode is:

$$J\frac{d^2\varphi_2}{dt^2} = M - Q \cdot f \cdot R. \qquad (14)$$

The solution of equation (14):

$$\varphi_2 = \frac{M \cdot t^2}{2 \cdot J} - \frac{Q \cdot f \cdot R \cdot t^2}{2 \cdot J} + C_1 \cdot t + C_2. \qquad (15)$$

If t = 0, $\phi_2 = 0$, then $C_2 = 0$.

To compute C_1, let us find an expression for the angular velocity:

$$\dot{\varphi}_2 = \frac{M \cdot t}{J} - \frac{Q \cdot f \cdot R \cdot t}{2} + C_1. \qquad (16)$$

The initial condition is that the angular velocity $\dot{\phi}_2$ at t = 0 is equal to the angular velocity ω_1 at the moment when adhesion is lost. This follows from the assumption that the mean angular velocity of the wheel set during braking must, over a small period of time, be constant, i.e.: ω_0 = const.

This is shown in Pic. 2. The angular velocity ω_1 is plugged into equation (16), i.e. $\dot{\phi}_2 = -\omega_1$.

Now the initial condition takes the form:

If t = 0; $\dot{\phi}_2 = \omega_1$;; $C_2 = -\omega_1$, (17)

then we get

$$\dot{\varphi}_2 = \frac{M \cdot t}{J} - \frac{Q \cdot f \cdot R \cdot t}{J} - \omega_1. \qquad (18)$$

Further, we have:

$$2 \cdot \omega_1 = \frac{M \cdot t_2}{J} - \frac{Q \cdot f \cdot R \cdot t_2}{J}. \qquad (19)$$

Let us find the time of sliding t_2. Assume the kinetic friction coefficient f = 0.15.

From the previous example, $\omega_1 = 0.21\ sec^{-1}$;

$$t_2 = \frac{2 \cdot \omega_1 \cdot J}{M - Q \cdot f \cdot R} = \frac{2 \cdot 0.21 \cdot 400}{2.5 \cdot 10^4 - 22 \cdot 10^4 \cdot 0.15 \cdot 0.5} = 0{,}02 \text{ sec.}$$

A point on the wheel's rim, at the train's speed V will travel the distance:

$\alpha_2 = V \cdot t_2$.

At V = 10 m/sec (or 36 km/h):

$\alpha_2 = 10 \cdot 0.02 = 0.2$ m.

Thus, the length of the valley in wavelike wear is: $\alpha_2 = 0.2$ m.

On the whole, the wavelength in our example at the speed of V = 10 m/sec:

$\alpha = \alpha_1 + \alpha_2 = 0.067 + 0.2 = 0.267$ m.

As stated in [7, page 47], before grinding more than 61 % of rail irregularities have wavelengths between 0.3 and 0.6 m. The results presented in our example (wavelength 0.267 m) are quite close.

Conclusions

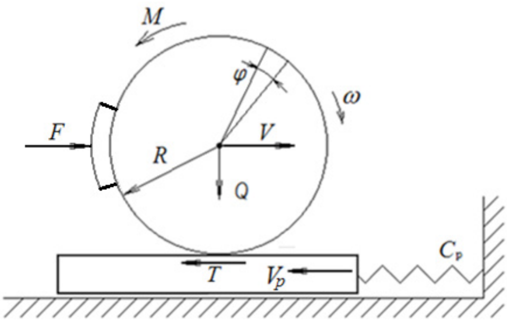
1. Braking remains one of the causes of corrugation wear of rails.

2. The immediate cause of wavelike rail wear is the periodic nature of wheel sliding on the rail, which is related to the fact that the wheel-rail interaction system is an oscillatory system [8].

3. In wavelike wear, the wavelength depends on the speed of trains and increases with increasing train speeds.

4. The speed of sliding and therefore the intensity of rail wear depend on the value of braking torque; as the braking torque grows, so do the consequences.

5. The speed of sliding depends on the health of the rail track; as the health deteriorates, sliding becomes more pronounced.



Pic. 3. Computational model of the «wheel set – rail track» system during slipping.

REFERENCES

1. Guidelines on current maintenance of railway tracks [*Directive po tekushschemu soderzhaniu puti*], as amended by Directives No. 950 of 30.05.2000 (23456789) TsP-774 of the Ministry of Railways of Russia.

2. Harris, W. J., Zakharov, S. M., Langren, J., Turne, H., Ebersen, V. Summarizing heavy-haul best practices: wheel-rail interactions [Translated from English. Russian title: *Obobscchenie peredovogo opyta tyazhelovesnogo dvizhenoya: voprosy vzaimodeastviya kolesa i relsa*]. Moscow, Intext, 2002, 408 p.

3. Schiller, A. V. Assessing the performance of grinded rail running surface [*Otsenka effektivnosti shlifovki poverhnosti kataniya relsov*]. *Omsk Research Bulletin. Instruments, machines and technologies series*, 2012, Iss. 2, pp. 111–115.

4. Koulagin, M. I., Katz, E. I., Tyurikov, V. N. Corrugation wear of rails [*Volnoobraznyi iznos relsov*]. Moscow, Transport Publ., 1970, 145 p.

5. Lazarian, V. A., Danovich, V. D., Manashkin, L. A. Forced vibrations of railcars on periodic track irregularities [*Vinuzhdennye kolebaniya vagonov po periodicheskim nerovnostiam puti*]. *Proceedings of DIIT*, 1969, Iss. 99, pp. 26–31.

6. Gozbenko, V. E., Kargapoltsev, S. K., Kornilov, D. N., Minaev, N. V., Karlina, A. I. Definition of the main coordinates of the car with two-level spring suspension. *International Journal of Applied Engineering Research*, 2016, Vol. 11, Iss. 20, pp. 10367–10373.

7. Timofeyeva, L. A., Ogoulchanskaya, N. R. Causes of corrugation wear of rail running surfaces in a rail track and methods of correction [*Prichiny vozniknoveniya volnoobraznogo iznosa poverhnosti kataniya rels zheleznodorozhnogo puti i metody ego ustraneniya*]. *Informatsionno-keruuchi sistemy na zaliznichnomu transporti* [Information processing systems in railway transport], 2015, Iss. 3, pp. 56–58.

8. Novoseltsev, V. P., Novoseltsev, P. V., Gordeeva, A. A. Impact of Longitudinal Stiffness of Rail Track on the Sliding of Locomotive Wheel Pair. *World of Transport and Transportation*, 2013, Iss. 4, pp. 34–38.

Information about the authors:
Kargapoltsev, Sergey K. – D.Sc. (Eng), professor, first deputy rector of Irkutsk State University of Railway Engineering, Irkutsk, Russia, kck@irgups.ru.
Novoseltsev, Petr V. – Ph.D. (Eng), associate professor of Ulan-Ude Railway Institute, a branch of Irkutsk State University of Railway Engineering, Irkutsk, Russia, nov-pv@mail.ru.
Kuptsov, Yuri V. – Ph.D. Student, senior lecturer of Ulan-Ude Railway Institute, a branch of Irkutsk State University of Railway Engineering, Irkutsk, Russia, yourakupcov@mail.ru.

Article received 08.05.2017, accepted 24.07.2017.