Determination of cutting modes when turning railway wheelsets used in heavy traffic

D.P. Kononov[1*] and *E.A.* Karaulshchikova[1]

[1]Emperor Alexander I St. Petersburg State Transport University, 190031, 9 Moskovsky pr., Saint Petersburg, Russia

Abstract. Increasing the durability of the cutting tool when restoring the profile of the rolling surface of railway wheels by controlling the vibrations of the machine-tool-part system. Vibrations arising during the turning of the rolling surface of wagon wheels under various cutting modes were studied. To do this, a matrix of experimental planning was built using the Box-Wilson method, according to which all factors change in turn (cutting depth, cutting speed, feed). After the experiment, a mathematical model is selected and the numerical values of the coefficients of this equation are estimated. In accordance with the power dependences accepted in the theory of cutting, a mathematical model was constructed for the experiments in the form of a logarithmic polynomial of the first degree series. Mathematical processing of measurement results using fractal dimension was carried out. The fractal dimension was determined by the normalized span method. A correspondence has been established between the durability of the he cutter and the intensity of its vibrations when turning railway wheels. A mathematical dependence of the fractal dimension on the cutting modes is obtained, which makes it possible to adjust the cutting speed or feed during the restoration of the rolling surface of the wheel in the presence of defects. Optimal cutting modes, which allow to achieve a given quality of the rolling surface of the wheel in the shortest possible time, give the highest value of fractal dimension. Defects in railway wheels such as sliders, bumps, and gouges lead to a decrease in fractal dimension. The determination of the fractal dimension in the process of turning wheelsets makes it possible to automatically adjust the cutting modes to ensure a given quality of the rolling surface of the wheel and the required durability of the cutting tool.

1 Introduction

Railway wheels are a responsible, heavily loaded element of rolling stock. Reliability and safety of operation largely depend on them. When organizing heavy traffic by rail, their working conditions are becoming more and more difficult [1-4].

The rolling surface profile, as defined by the relevant standard, has a significant impact on the reliability and durability of the wheels. The GOST 10791-2011 specification imposes strict requirements on the dimensional accuracy of railway wheels and the roughness of their surfaces, which can only be achieved through machining with specific features. These

* Corresponding author: d_kononov@mail.ru

features include fluctuations in the machining allowance due to both the unique characteristics of the wheel profile and wear during operation. Additionally, there are significant variations in the hardness of the machined material, depending on the carbon content in the melt and the characteristics of the workpiece production process, the presence of defects in the rolling surface. All this negatively affects the cutting conditions during wheel turning during repair, and, as a result, reduces the durability of the cutting tool and increases the processing time [5-7]. Reducing the durability of the tool leads, in turn, to an increase in the cost of sharpening carbide plates, as well as the purchase of new ones. In addition, the time for tool replacement increases. Because of this, the performance of restoring the rolling surface of the wheels is reduced.

The main criterion for the machinability of any materials is the cutting speed allowed by the cutting tool with a certain resistance and other constant parameters.

The best wheel machining processes (the highest resistance of carbide plates, the best quality of the treated surface) are observed when the tangential component of the cutting force Pz = f(v), is stabilized while maintaining constant cutting depth t, feed S and geometry of the cutting tool.

It is known that the mechanical and physical properties of the tool depend on fluctuations in the machine-tool-part system during the cutting process [8-11]. Changing the processing conditions only changes the nature of the oscillation spectrum of the system, the level of its individual frequency components [6-8]. In [9], it was found that for each oscillation frequency there are some critical amplitude values, exceeding which leads to a sharp decrease in tool durability. The higher the oscillation frequency, the lower the critical amplitude values. The values of the critical oscillation amplitudes that occur when processing steel 45 with a hardness of 190 HB тwith a hard alloy of the T15K6, grade are shown in Table 1. Cutting mode: $V = 2{,}15$ m/s, $S = 2\cdot10^{-4}$ m/r, $t = 5\cdot10^{-4}$ m.

Table 1. Values of critical oscillation amplitudes

Oscillation frequency, kHz	10…15	7…10	3,5…4,5	2…3
The amplitude of the oscillations, m	$(7…9)\cdot10^{-8}$	$(9…10)\cdot10^{-8}$	$(2…4)\cdot10^{-7}$	$(8…12)\cdot10^{-7}$

The extreme dependence of the durability of the cutting tool on the amplitude of vibrations in the frequency range from 150 to 3000 Hz is determined by the formula [10]:

$$T = \Theta \cdot A^m \cdot e^{-nA},$$

where T is the durability of the cutting tool, min.;
A is the amplitude of vibrations, microns;
Θ, m, n are constants depending on the type of processed and tool material and cutting conditions.

This dependence is the result of the influence of two opposite factors: a decrease and an increase in tool wear at different vibration intensities. For example, the cutting force and friction in the cutting area decrease with increasing vibrations. But at the same time, vibrations of the cutting tool lead to fatigue destruction of its cutting edges.

Such a dependence $T = f(A)$ means that for each specific technological process there is a certain optimal (by the criterion of durability) oscillation amplitude, at which the greatest tool durability takes place.

Based on this, it can be said that the management of dynamic processes that occur during the turning of railway wheels is an urgent task.

The purpose of this work is to develop a methodology for controlling dynamic processes in restoring the profile of the rolling surface of railway wheels by controlling vibrations of the machine-tool-part (MTP) system.

2 Materials and methods

A fractal dimension was used to determine the relationship between the vibration of the cutting tool and its durability. This is one of the modern methods that allows you to determine the features of random structures [12]. The larger the fractal dimension, the higher the vibrations. There are several methods for determining fractal dimension. In this work, the normalized span method was used, which is based on the definition of the Hurst index.

The fractal dimension:

$$D = 2 - H,$$

where H – the Hurst index. It is defined from the expression:

$$R(\tau)/S(\tau) \sim \tau^{H},$$

where R – the magnitude;

S – the standard deviation:

$$S(\tau) = \sqrt{\frac{1}{\tau}\sum_{t=1}^{\tau}\{\xi(t) - \langle\xi\rangle_{\tau}\}^{2}};$$

τ – is the value of the time interval.

Figure 1 shows an example of determining the fractal dimension in coordinates *R/S*(τ). The curve is plotted on a double logarithmic scale, after which a linear approximation is performed. The Hurst exponent is the tangent of the angle of inclination of the resulting straight line.

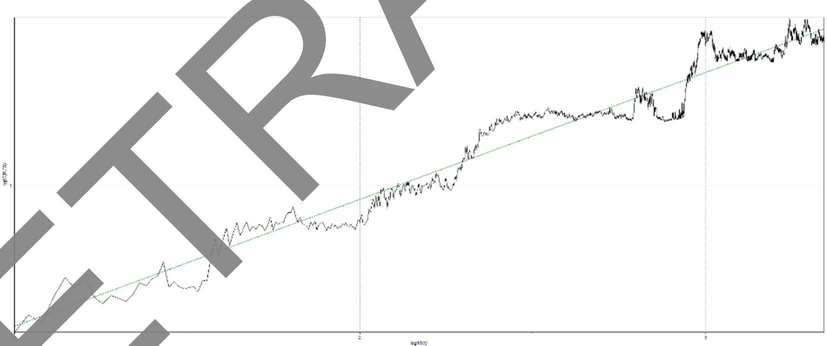

Fig. 1. An example of the definition of fractal dimension

Approximately, the Hurst index can be determined by the least squares method using the formula:

$$\ln\left(\frac{R}{S}\right) = \ln(c) + H \cdot \ln(n),$$

where c is a measure of correlation;

n is the number of observations.

The dependence of the fractal dimension on the cutting depth, feed and cutting speed is expressed by a formula like:

$$D(t, S, V) = C_D \cdot t^{x_D} \cdot S^{y_D} \cdot V^{z_D}, \quad (1)$$

where C_D – is a constant coefficient;

x_D, y_D, z_D- indicators of the degree of influence of cutting depth, feed and cutting speed on the fractal dimension.

To obtain this dependence, the method of a complete factorial experiment [13-15] was used, the *basis* of which is regression analysis, which allows translating a power function of a polynomial of the form

$$\hat{y} = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 \tag{2}$$

with regression *coefficients* b_0, b_1, b_2, b_3,
where X_1, X_2, X_3 – factors converted to dimensionless variables:

$$\left.\begin{aligned} X_1 &= \frac{2\cdot(\ln t - \ln t_{max})}{\ln t_{max} - \ln t_{min}} + 1; \\ X_2 &= \frac{2\cdot(\ln S - \ln S_{max})}{\ln S_{max} - \ln S_{min}} + 1; \\ X_3 &= \frac{2\cdot(\ln V - \ln V_{max})}{\ln V_{max} - \ln V_{min}} + 1. \end{aligned}\right\} \tag{3}$$

$\ln D = \hat{y}, \ln C_D = b_0, x_D = b_1, y_D = b_2, z_D = b_3$.

Table 2 shows the lower and upper levels of factors determining the range of variation.

Table 2. Factor values and variation intervals

Parameters	Unit of measurement	Factor levels	
		lower	upper
t	mm	4	5
S	mm/r	0,7	1,3
V	rpm	9,6	12,8

The half-difference between the values of the upper and lower levels of factors is taken as a unit of *t*, *S*, *V*: the value $(\ln 5 - \ln 4)/2$ is taken as a unit of cutting depth, $(\ln 1{,}3 - \ln 0{,}7)/2$ is taken as a unit of feed, and $(\ln 12{,}8 - \ln 9{,}6)/2$. Thus, the depth, feed and speed of the rubber are converted by dividing them into accepted units.

$$\left.\begin{aligned} b_0 &= (\textstyle\sum X_{0i} \cdot \bar{y}_i)/N; \\ b_1 &= (\textstyle\sum X_{1i} \cdot \bar{y}_i)/N; \\ b_2 &= (\textstyle\sum X_{2i} \cdot \bar{y}_i)/N; \\ b_3 &= (\textstyle\sum X_{3i} \cdot \bar{y}_i)/N, \end{aligned}\right\} \tag{4}$$

where *N* is the number of options, *N* = 8;
$\bar{y}_i$ is the average value of the experimental result in the *i*-th experiment;
$X_{0i}, X_{1i}, X_{2i}, X_{3i}$ – the level of factors X_0, X_1, X_2, X_3 in the first experiment. The dummy variable $X_0 = +1$. Factor levels instead of +1 and -1 are written as "+" and "-" (see Table 3).

The experiment was planned according to the rule of the "Italian cube" (Fig. 2). The vertices of the cube are the cutting modes used in the experiment.

As a result, we get an expression of the form

$$\ln D = \ln C_D + x_D \cdot \ln t + y_D \cdot \ln S + z_D \cdot \ln V,$$

having tested which, we obtain the equation (1).

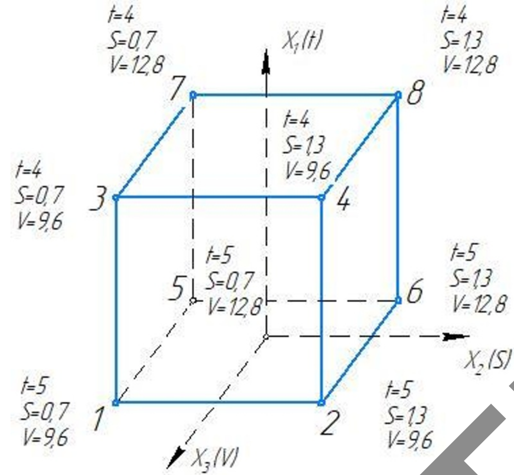

Fig. 2. Research plan according to the "Italian cube"

3 Results

To determine the fractal dimension, an experiment was conducted to measure vibrations occurring during the turning of wheelsets in various cutting modes in the presence of defects and without them using multifactor analysis. To do this, each of the cutting mode parameters (cutting depth, feed and speed) were set to two values – the largest and the smallest (Table 2).

Wheels of GOST 10791-2011 grade 2 with and without skating surface defects were processed. The wheel turning machine UBB-112 was used for turning. A tangential plate LNUX 301940 23 made of a hard alloy of the KS-35 brand was used as a cutting tool.

A two-channel diagnostic vibration analyzer KON.TEST C9000 with CTC AC102-1A piezoelectric vibration sensors was used to measure vibrations (Fig. 2). The vibration sensor was attached to the cutter holder using a magnet.

Fig. 2. Vibration analyzer KON.TEST C9000 with CTC AC102-1A vibration sensors

The calculation results are shown in Table 3.

Table 3. The experimental plan and the results of the fractal dimension calculation

Experience number	X_0	X_1		X_2		X_3		The average value of the fractal dimension $\overline{D}$
	code	code	t, mm	code	S, mm/r	code	V, rpm	
1	+	+	5	-	0,7	-	9,6	1,42065
2	+	+	5	+	1,3	-	9,6	1,44905
3	+	-	4	-	0,7	-	9,6	1,3781
4	+	-	4	+	1,3	-	9,6	1,36521
5	+	+	5	-	0,7	+	12,8	1,39264
6	+	+	5	+	1,3	+	12,8	1,30417
7	+	-	4	-	0,7	+	12,8	1,46166
8	+	-	4	+	1,3	+	12,8	1,37678

Substituting the experimental results into formulas (4), we obtain:
$b_0 = 0{,}3313$;
$b_1 = -\ 0{,}00156$;
$b_2 = -\ 0{,}01439$;
$b_3 = -\ 0{,}00724$.
Then the equation of the model (2) will be written as follows:

$$\hat{y} = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 = 0{,}3313 - 0{,}00156 \cdot X_1 - 0{,}01439 \cdot X_2 - 0{,}00724 \cdot X_3.$$

To obtain equation (1) in the natural values of the factors, it is necessary to substitute their values from the conversion formulas (3) instead of X_1, X_2, X_3 and then perform potentiation:

$$\ln D = 0{,}3313 - 0{,}00156 \cdot \left(\frac{2\cdot(\ln t - \ln 5)}{\ln 5 - \ln 4} + 1\right) - 0{,}01439 \cdot \left(\frac{2\cdot(\ln S - \ln 1{,}3)}{\ln 1{,}3 - \ln 0{,}7} + 1\right) - 0{,}00724 \cdot \left(\frac{2\cdot(\ln V - \ln 12{,}8)}{\ln 12{,}8 - \ln 9{,}6} + 1\right) = 0{,}3313 - 0{,}01398 \cdot \ln t + 0{,}02094 - 0{,}04649 \cdot \ln S - 0{,}00219 - 0{,}05033 \cdot \ln V + 0{,}12108 =$$
$$= 0{,}47113 - 0{,}01398 \cdot \ln t - 0{,}04649 \cdot \ln S - 0{,}05033 \cdot \ln V.$$

After potentiation, we have:

$$D = e^{0{,}47113} \cdot t^{-0{,}01398} \cdot S^{-0{,}04649} \cdot V^{-0{,}05033}.$$

4 Analysis of the results

When analyzing the results, the reproducibility, significance and adequacy of the model were checked.

Reproducibility was assessed using the Cochran criterion. In this case, the variance at each point of the experiment was calculated:

$$s_i^2 = \frac{\sum_1^N (y_{qi} - \bar{y}_i)^2}{n-1},$$

where n is number of measurements;
y_{qi} – the result obtained in the relevant experience;
$\bar{y}_i$ – the average value of the response at a point in the matrix.

The Cochran criterion is the ratio of the largest variance obtained in experiments to the sum of the variances of all experiments:

$$G = \frac{s_{max}^2}{\sum_1^N s_i^2} = \frac{0{,}0159}{0{,}0655} = 0{,}2428.$$

The critical value of the Cochran criterion for the 5% significance level is G_{cr} = 0,2926. The hypothesis of uniformity of variance is accepted, since the experimental value of the criterion does not exceed the tabular one.

The significance was checked using the Student's criterion:

$$t = \frac{|b_i|}{s_{\{b\}}},$$

where $s_{\{b\}}$ – the standard deviation of the regression coefficients:

$$s_{\{b\}}^2 = \frac{s_{\{y\}}^2}{N}$$

where $s_{\{y\}}^2$ – the variance of reproducibility.

According to the results of the calculations, it was obtained that the coefficient b_0 is significant, and the coefficients b_1, b_2, b_3 – are insignificant. This indicates that vibrations during turning of wheelsets when using the above cutting modes depend mainly on the characteristics of the wheel steel (hardness, presence of rolling surface defects, etc.).

In order to understand how much the model predicts the results of the experiment, the Fisher criterion was used:

$$F = \frac{s_{ад}^2}{s_{\{y\}}^2},$$

where $s_{ад}^2$ – the variance of adequacy;

$s_{\{y\}}^2$ – the variance of reproducibility.

The variance of the adequacy $s_{ад}^2$ is called the residual sum of squares divided by the number of degrees of freedom f_1:

$$s_{ад}^2 = \frac{\sum_1^N \Delta Y_i^2}{f_1} = \frac{\sum_1^N (\bar{y}_i - \hat{y}_i)^2}{N-(k+1)},$$

where $\bar{y}_i$ – the average response value in the experiment;

$\hat{y}_i$ – is the response value predicted by the model based on the conditions of the experiment;

f_1 – is the number of degrees of freedom, which is the difference between the numbers of experiments and the coefficients that are calculated from the results of experiments independently of each other:

$$f_1 = N - (k+1),$$

where N – number of experiments;

$k + 1$ – the number of calculated coefficients.

The calculated criterion is compared with the tabular one. If $F < F_{table}$, then the model is adequate to the response function. In our case, the tabular value of the criterion $F_{table} =$ 2,18, and the calculated value is $F = 0{,}270764268$, therefore the model is adequate to the response function.

5 Conclusion

Analyzing the results obtained, the following conclusions can be drawn:

1. Optimal cutting conditions, which ensure a given level of wheel surface finish in the shortest possible time, yield the highest possible fractal dimension..

2. The presence of defects in railway wheels, such as sliders, bumps, dents, leads to a decrease in fractal dimension.

3. Vibration monitoring during the process of wheelset turning allows for automatic adjustment of cutting parameters to ensure a desired level of quality of the wheel's rolling surface and the required longevity of the cutting tool.

References

1. Ivanov, I., Evseev, D., Ovsyanikova, I., Tarapanov, A. sets (2017) Transport Problems, **12 (3),** 35-42. DOI: 10.20858/tp.2017.12.3.3.
2. Gubenko S., Ivanov I., Kononov D., Urushev S. 2020 IOP Conf. Ser.: Mater. Sci. Eng. **971** 052067. https://doi.org/10.1088/1757-899X/971/5/052067
3. Vorobev, A.A., Krutko, A.A., Shadrina, N.U., Badamshin, A.M. (2019) Journal of Physics: Conference Series**, 1260 (7),** 072019. DOI: 10.1088/1742-6596/1260/7/072019
4. Vorobev, A.A., Konogray, O.A., Krutko, A.A., Malakhov, I.I. (2020) Journal of Physics: Conference Series, **1441 (1),** 012127. DOI: 10.1088/1742-6596/1441/1/012127
5. Prokopev V.I., Zhdanova T.V., Kushkhov B.S. Advances in intelligent systems and computing, **982** (2020), pp. 603-614. DOI: 10.1007/978-3-030-19756-8_57
6. Boyang An, Ping Wang, Jieling Xiao, Jingmang Xu, Rong Chen. Shock and Vibration, vol. **2017**, Article ID 5634726, 11 pages, 2017. https://doi.org/10.1155/2017/5634726
7. Gavrilov, T., Kolesnikov, G., Khoroshilov, K. (2018) MATEC Web of Conferences, **239**, 05012. DOI: 10.1051/matecconf/201823905012
8. Blagoveshchenskaya, E.A., Gruzdev, N.V., Bochkarev, S.V., Zuev, D.V. (2020) CEUR Workshop Proceedings, **2556**, pp. 21-28.
9. Boronenko, Yu.P., Rahimov, R.V., Lafta, W.M., Dmitriev, S.V., Belyankin, A.V., Sergeev, D.A. *Continuous monitoring of the wheel-rail contact vertical forces by using a variable measurement scale* (2020) 2020 Joint Rail Conference, JRC 2020. DOI: 10.1115/JRC2020-8067
10. Paul Molyneux-Berry, Claire Davis, Adam Bevanhttps. (2014), The Scientific World Journal **2014(4):**209752 DOI: 10.1155/2014/209752.
11. Grachev, V.V., Grishchenko, A.V., Kruchek, V.A., Andreev, V.E., Kim, S.I., Fedotov, M.V. (2019) Russian Electrical Engineering, **90 (10),** 675-681. DOI: 10.3103/S1068371219100043
12. Kononov D., Gubenko S., Ivanov I., Urushev S. MATEC Web of Conferences, **329**, Article Number 02009 (2020). https://doi.org/10.1051/matecconf/202032902009
13. Okagata, Y., Kiriyama, K., Kato, T. Fatigue strength evaluation of the Japanese railway wheel // Fatigue and Fracture of Engineering Materials and Structures, Volume 30, Issue 4, April 2007, Pages 356-371. DOI: 10.1111/j.1460-2695.2007.01117.x
14. Vorobev, A., Kharlov, M. (2022). *Assessment of the Stress State and Strength of the Cutting Tool Used in the Rolling Stock Wheels' Repair.* In: Manakov, A., Edigarian, A. (eds) International Scientific Siberian Transport Forum TransSiberia - 2021. TransSiberia 2021. Lecture Notes in Networks and Systems, **vol 402**. Springer, Cham. https://doi.org/10.1007/978-3-030-96380-4_51
15. Gordienko, V., Chernykh, A. and Repin, S. (2020). E3S Web of Conferences, Vol. **164**, Article 08021. DOI: 10.1051/e3sconf/202016408021.