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Features of determining engagement line of traction gears with different degrees of wear of gear teeth

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Abstract. Calculations of strength, forecasting the residual operation life for repairing traction gears (TG) is carried out on the results of modeling their motion characteristic, which is based on the determined coordinates of the contact points of the gear and wheel profile for the period of engagement (engagement line). This article presents results of a study aimed at developing mathematical dependencies for a refined determination of TG engagement line with the established wear of gear teeth. Adequacy verification of proposed mathematical descriptions was carried out based on the results of the study of new TG of ER-2 electric train series. Their comparison with the coordinates of the engagement line, calculated by the traditional method, showed that modelling uncertainty does not exceed 0.06%. As an example of practical use of the received mathematical descriptions, results of research of motion characteristic of new TG of ER-2 electric train series with the established degrees of wear of gear and wheel teeth are presented.

1. Introduction

Mainly traction rolling stock (TRS) and multiple-unit train (MU) with excessive service life carry out a significant amount of traffic on Ukrzaliznytsia PJSC (Ukrainian Railways) networks. Therefore, strategy for the development of railway transport for the period up to 2020 (approved by the Order of Cabinet of Ministers of Ukraine No. 51555-r on December 16, 2009) and the State Program for rolling stock renewal for 2017-2021 (approved at a meeting of Ukrzaliznytsia PJSC on November 29, 2016) provide for upgrades, as well as extension of the service life of existing rolling stock on the basis of relevant research and development work. One of the areas of such research is to ensure the reliability, technical resource of the main modules of TRS and MU [1]. These include the traction drive as a whole and the traction gear (TG) functioning in its structure.

2. Recent research and publications analysis

Experience of TG repairs has shown that due to extreme wear of gear teeth, more than 90% of gears and about 60% of wheels are rejected prematurely [2]. That is, wear features of the active surfaces of the teeth should be considered one of the main factors influencing TG technical resource, which significantly depends on the resource of the traction drive [3].

According to the results of researches performed, it is established that operational wear of active profiles of gear and wheel teeth cause essential changes in engagement characteristics of functioning TG (in comparison with new gear) [4]. Distortion of profile configuration in normal sections due to wear leads to a violation of the main property of involute gearing, which consists in conversion of rotational motion from gear to wheel with a constant gear ratio ($i_{12} = -\omega_1 / \omega_2 = const$). This causes significant additional dynamic loads, reducing TG technical resource, increasing the levels of bending stresses of the teeth and contact stresses in the gear [5,6]. Therefore, the calculations of TG strength with different degrees of teeth wear involves determining the nature of the change in the value of the gear ratio (gear ratio $u_{12} = |i_{12}|$) during the period of gear pair catching. In addition, ensuring the rational formation of TG repair [4] requires the development of sound recommendations, based on the results of modeling the characteristics of gear transmission with different degrees of teeth wear of active profiles over the entire height – that is, the actual value of the overlap coefficient, patterns of change in the coefficients of specific sliding and pressure for the period of teeth pair engagement.

The key point of such works is the specified definition of the current coordinates of the contact point's trajectory of the real profiles of the teeth for the period of their engagement (engagement lines). At this time, the problem of obtaining digital descriptions of the considered real profiles of teeth with different degrees of wear has been solved at a sufficiently high level [7, 8]. Nevertheless, modeling their engagement characteristics at best is carried out mainly using graphical methods [9]. At the same time in the special scientific and technical literature, the issue of analytical research of TG engagement characteristics with the established wear of gear and wheel teeth with the use of other methods are insufficiently covered.

3. Defining the aim and objectives of this investigation

The aim of this investigation is to develop mathematical dependences to solve the problem of determining TG engagement line with different degrees of wear of gear and wheel teeth.

To achieve this aim, the following tasks were solved:

1. Development of mathematical descriptions that provide determination of the boundary points of teeth contact (position of gear and wheel teeth axes t the beginning and end of engagement).
2. Obtaining mathematical dependences to determine the coordinates of the current points of contact in the teeth engagement.

4. The main part of the study

In order to solve the first issue to determine the position of the axes of worn gear and wheel teeth of TG at the beginning (contact point B_1 at figure 1 at the intersection of radii circles r_{a2} and r_{B_1}, angles in question are $\psi_{1\Pi}$, $\psi_{2\Pi}$) and end of engagement (contact point B_2 at figure 1 at the intersection of radii circles r_{a1} and r_{B2}, angles in question are ψ_{13}, ψ_{23}), the method of projections of closed vector contours on the coordinate axis was used (V.A. Zinoviev's method) [10].

Therefore, in relation to TG, a coordinate system $X_0O_1Y_0$ was introduced, and gear geometric parameters r_{a1}, r_{a2}, r_{B_1}, r_{B2}, a_w were replaced by the corresponding vectors $\bar{r}_{a1}$, $\bar{r}_{a2}$, $\bar{r}_{B1}$, $\bar{r}_{B2}$, $\bar{a}_w$. For the moments of the beginning and the end of engagement of gear and wheel teeth vector contours $O_1B_1O_2O_1$ and $O_1B_2O_2O_1$ were considered, for which conditions of closeness are considered

$$\bar{r}_{B_1} + \bar{r}_{a2} = \bar{a}_w; \quad \bar{r}_{B_2} + \bar{r}_{a1} = \bar{a}_w. \tag{1}$$

Formulas for determining the desired angles that define the position of the axes of gear and wheel teeth at the moments of their engagement are obtained from the transformation of equation projections (1) on the coordinate axis O_1X_0 and O_1Y_0

$$\psi_{1\Pi} = \varphi_{1\Pi} + \arcsin[\bar{s}_{B_1}/(2 \cdot r_{B_1})]; \quad \psi_{2\Pi} = \varphi_{2\Pi} - \arcsin[\bar{s}_{a2}/(2 \cdot r_{a2})], \tag{2}$$

where $\varphi_{1\Pi} = \arccos[(a_w^2 + r_{B_1}^2 - r_{a2}^2)/(2 \cdot a_w \cdot r_{B1})]$; $\varphi_{2\Pi} = \arccos[\sqrt{1-(r_{B_1}\sin\varphi_{1\Pi}/r_{a2})^2}$,

$$\psi_{13} = \varphi_{13} - \arcsin[\bar{s}_{a_1}/(2 \cdot r_{a_1})]; \quad \psi_{23} = \varphi_{23} + \arcsin[\bar{s}_{B2}/(2 \cdot r_{B2})], \tag{3}$$

where $\varphi_{13} = \arccos[(a_w^2 + r_{a1}^2 - r_{B_2}^2)/(2 \cdot a_w \cdot r_{a1})]$; $\varphi_{23} = \arccos[\sqrt{1-(r_{a1}\sin\varphi_{13}/r_{B_2})^2}$.

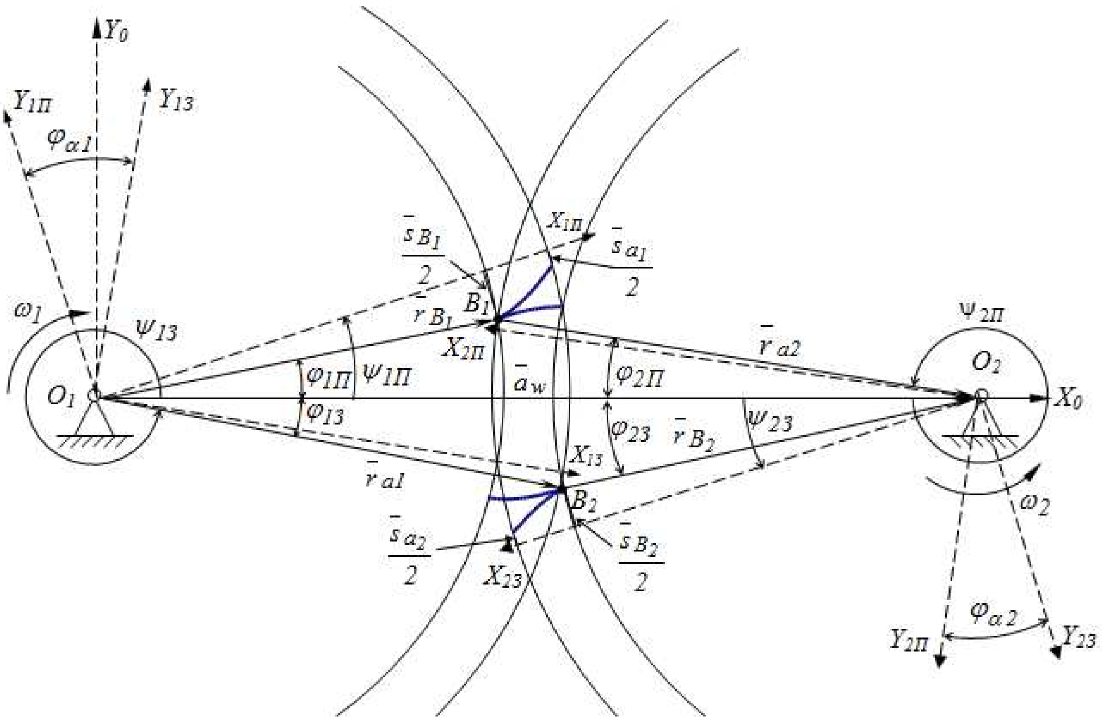

Figure 1. Before determining axes limit positions of worn gear and wheel teeth of TG.

Analytical dependences for determining the coordinates in the system $X_0O_1Y_0$ of current contact points of the teeth profiles with the established thicknesses of the circles chords of the corresponding radii of the gear and wheel (the second task of this investigation) were obtained on the basis of coordinate transformation method (G.F. Moroshkin's method) [11]. Figure 2 shows a fragment of TG motion scheme. Gear 1 and wheel 2, together with rack 0 form rotating motion pairs of the fifth class O_1, O_2.

The working profiles of the teeth form the highest motion pair of the fourth class B (contact point). Coordinates of the flow point of contact B in the coordinate system $X_1O_1Y_1$: $x_1 = O_1A_1 = l_{e1}$; $y_1 = A_1B = \bar{S}_{e1}/2$ ($\bar{S}_{e1}$ is thickness of the gear tooth, determined at a distance l_{e1} from rotation center O_1). Coordinates of the flow point of contact B in the coordinate system $X_2O_2Y_2$: $x_2 = O_2A_2 = l_{e2}$; $y_2 = A_2B = \bar{S}_{e2}/2$ ($\bar{S}_{e2}$ is thickness of the gear tooth, determined at a distance l_{e2} from rotation center O_2).

The matrix notation of equation system for the transformation of the point coordinates is the following

$$r_i = T_{ji} \cdot r_j, \quad (4)$$

where r_i is matrix-column of point coordinates in the basic coordinate system; r_j is matrix-column of point coordinates in a new coordinate system; T_{ji} is matrix of equation coefficients.

Equation matrix (4) to determine in the system $X_0O_0Y_0$ the coordinates of point B, which belongs to gear and wheel teeth, respectively

$$r_0 = \begin{Vmatrix} x_0 \\ y_0 \\ 0 \end{Vmatrix}, \quad r_1 = \begin{Vmatrix} l_{e1} \\ \bar{S}_{e1}/2 \\ 0 \end{Vmatrix}, \quad T_{10} = \begin{Vmatrix} \cos\psi_{01} & -\sin\psi_{01} & 0 \\ \sin\psi_{01} & \cos\psi_{01} & 0 \\ 0 & 0 & 1 \end{Vmatrix}; \tag{5}$$

$$r_0 = \begin{Vmatrix} x_0 \\ y_0 \\ 0 \end{Vmatrix}, \quad r_2 = \begin{Vmatrix} l_{e2} \\ \bar{S}_{e2}/2 \\ 0 \end{Vmatrix}, \quad T_{20} = \begin{Vmatrix} \cos\psi_{02} & -\sin\psi_{02} & a_w \\ \sin\psi_{02} & \cos\psi_{02} & 0 \\ 0 & 0 & 1 \end{Vmatrix}. \tag{6}$$

According to G.F. Moroshkin's method, the issue of determining the positions of TG gear and wheel for the corresponding contact point coordinates of the real profiles of the teeth is reduced to the joint solution of equations obtained from formulas (5), (6) with conditional opening of motion pair *B*.

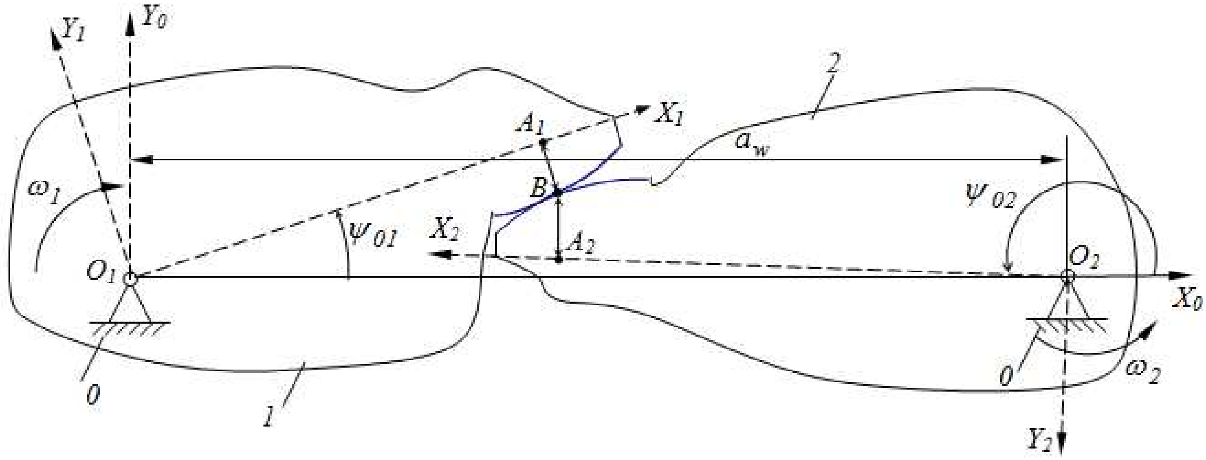

Figure 2. Before determining the coordinates of the current contact points of the profiles of the gear and wheel teeth of TG.

Then the conditions for the existence of the current contact point of the profiles of gear and wheel teeth are the equations

$$l_{e1} \cdot \cos\psi_{01} - (\bar{S}_{e1}/2) \cdot \sin\psi_{01} = l_{e2} \cdot \cos\psi_{02} - (\bar{S}_{e2}/2) \cdot \sin\psi_{02} + a_w; \tag{7}$$

$$l_{e1} \cdot \sin\psi_{01} + (\bar{S}_{e1}/2) \cdot \cos\psi_{01} = l_{e2} \cdot \sin\psi_{02} + (\bar{S}_{e2}/2) \cdot \cos\psi_{02}. \tag{8}$$

The use of the obtained mathematical dependences in TG investigation requires analytical descriptions of active profiles of gear and wheel teeth of the following type

$$\bar{S}_{e1}/2 = f(l_{e1}), \quad l_{e1} \in [r_{B_1}; r_{a1}]; \tag{9}$$

$$\bar{S}_{e2}/2 = f(l_{e2}), \quad (l_{e2} \in [r_{B_2}; r_{a2}]). \tag{10}$$

Studies have shown that in the presence of the results of experimental determination of teeth thickness according to the chords of respective circles to develop such descriptions, it is advisable to use the Lagrange interpolation formula [12].

Analytical dependences (7) to (10) are the basis for the study of the characteristics of worn TG engagement with the established thicknesses of gear and wheel teeth according to the circle chords of corresponding radii. When fixing the angle value $\psi_{01} \in [\psi_{1\Pi}; \psi_{13}]$ and the stepwise angle setting $\psi_{02} \in [\psi_{2\Pi}; \psi_{23}]$ (angles are calculated in accordance with figure 2), the coordinates of the corresponding contact point (X_0,Y_0) in the system $X_0O_0Y_0$, which satisfy conditions (7), (8), are determined by iterative approximations.

In order to verify the adequacy of the proposed mathematical descriptions, a calculated study of a new TG electric train EP-2 series (number of gear teeth $z_1 = 23$ and wheel teeth $z_2 = 73$; teeth modules $m = 10$ mm; intercenter distance $a_w = 485$ mm; gear displacement coefficient $x_1 = 0.478$ and wheel displacement coefficient $x_2 = 0.041$), aimed at determining the coordinates of the current contact points of gear and wheel teeth during the period of their engagement. A comparison of the obtained results with the coordinates of the engagement line B_1B_2, calculated by the traditional method (Figure 3) showed that modelling uncertainty does not exceed 0.06%. Such results substantiate the possibility and expediency of using the proposed approach as well as the developed mathematical support in the study of the characteristics of TG engagement with different degrees of teeth wear.

Below are the results of the study of the kinematics of TG electric train EP-2 series with the established degrees of teeth wear (digital images of gear and wheel teeth are presented in Figure 4). Engagement line B_1B_2 of the studied TG, obtained using the developed mathematical descriptions, is shown in Figure 5 below. A comparison of the obtained results with experimental data [9] showed that modelling uncertainty does not exceed 1%.

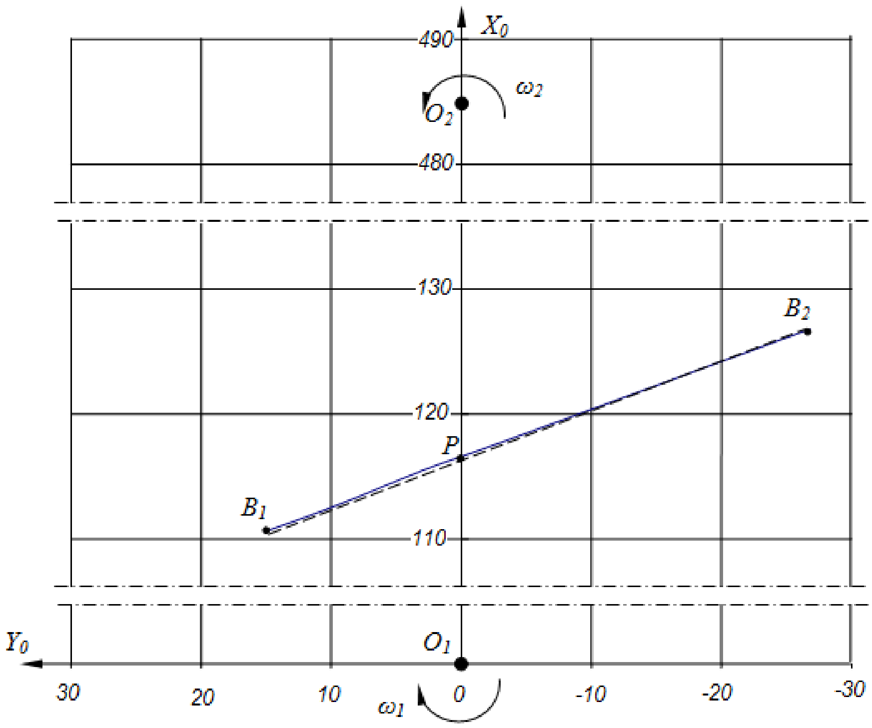

Figure 3. Results of modeling coordinates of the current contact points of the active teeth profiles for the period of engagement of the new TG electric train EP-2 series: --------- using the traditional method; using the developed ———— mathematical dependences.

During this investigation, when determining the coordinates of each i-th contact point within $X_0O_1Y_0$ system of active profiles of gear and wheel teeth (X_0, Y_0), the increment of the wheel rotation angle $\Delta\psi_{02_i} = \psi_{02_i} - \psi_{02_{i-1}}$ was determined for each given increment of the gear rotation angle $\Delta\psi_{01_i} = \psi_{01_i} - \psi_{01_{i-1}}$. This allowed determining the current value of the gear ratio u_{12} and the angular velocity analog ω_{q2} for the corresponding TG position

$$u_{12i} = \frac{\Delta\psi_{01i}}{\Delta\psi_{02i}}, \quad (11)$$

$$\omega_{q2i} = \frac{1}{u_{12i}}. \quad (12)$$

Figure 6 presents graphs of changes in gear ratio u_{12}, angular velocity analogues ω_{q2} and angular acceleration ε_{q2} depending on $\Delta\psi_{01}$ for the studied TG (graph $\varepsilon_{q2} = f(\Delta\psi_{01})$, obtained from the graph $\omega_{q2} = f(\Delta\psi_{01})$ by the method of finite differences [13]).

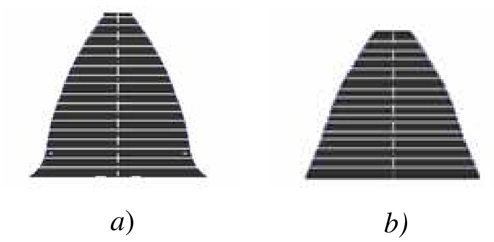

Figure 4. Digital images of active profiles of gear teeth (*a*) and wheel teeth (*b*) of studied TG.

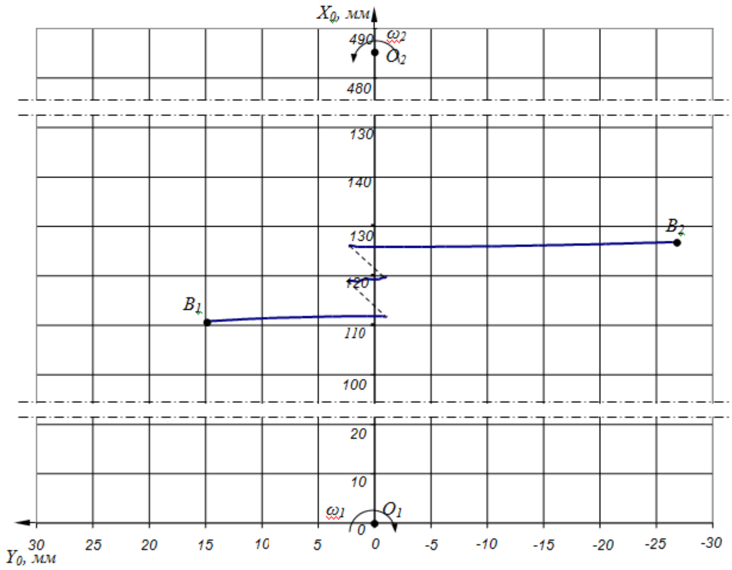

Figure 5. Engagement line of studied TG.

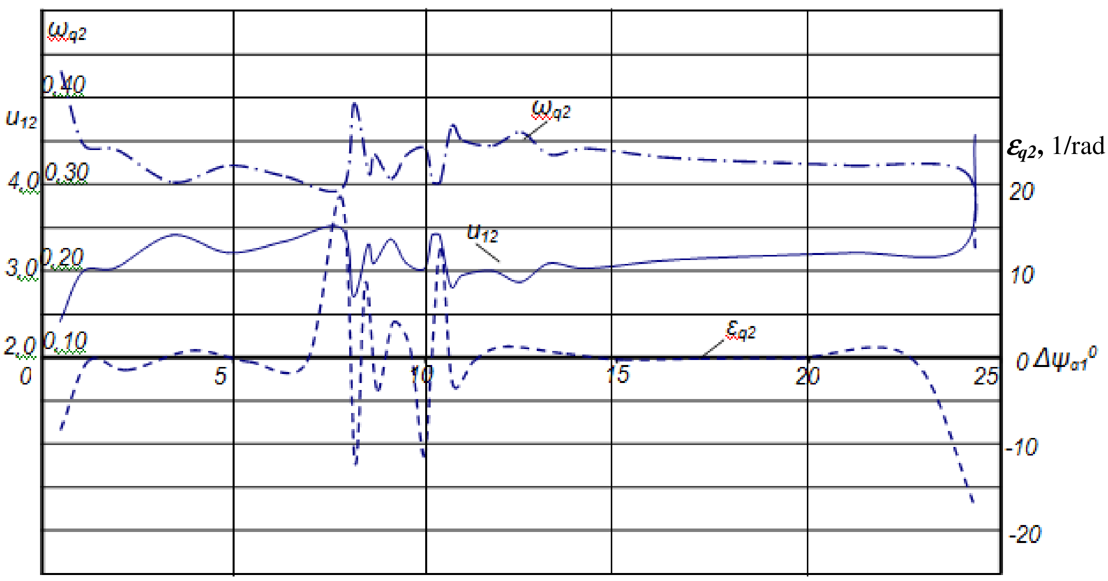

Figure 6. Results of studying of TG electric train ER-2 motion with the established degrees of gear and wheel wear

Such results are considered the basis for further investigation of TG with the established degrees of gear and wheel wear.

5. Conclusions

Analysis of the presented results proves the expediency of using the developed mathematical dependences to determine the contact points of the teeth, lines and gears, which is important for predicting TG strength and residual life.

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