Розроблено систему інноваційної діагностики хрестовин стрілочних переводів. Проведено експериментально-теоретичні дослідження поздовжнього профілю хрестовин стрілочних переводів залізничної колії, укладених на залізобетонних брусах. Установлено характерні траєкторії руху центра мас колеса по хрестовині залежно від зносу вусовиків та осердя хрестовини. Розроблено математичну модель прогнозування зносу профілю хрестовин залежно від пропущеного тоннажу

Ключові слова: хрестовина, стрілочний перевід, поздовжній профіль, траєкторія руху, рухомий склад залізниць

Разработана система инновационной диагностики крестовин стрелочных переводов. Проведены экспериментально-теоретические исследования продольного профиля крестовин стрелочных переводов железнодорожного пути, установленных на железобетонных брусьях. Установлены характерные траектории движения центра масс колеса по крестовине в зависимости от износа усовиков и сердечника крестовины. Разработана математическая модель прогнозирования износа профиля крестовин в зависимости от пропущенного тоннажа

Ключевые слова: крестовина, стрелочный перевод, продольный профиль, траектория движения, подвижной состав железных дорог

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DEVELOPMENT OF A PROMISING SYSTEM FOR DIAGNOSING THE FROGS OF RAILROAD SWITCHES USING THE TRANSVERSE PROFILE MEASUREMENT METHOD

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1. Introduction

The railroads of Ukraine currently operate more than 50 thousand railroad switches and blind intersections. Most of them (98 %) are single ordinary railroad switches.

Basic railroad switches that are most common on the railroads of Ukrzaliznytsia after 1990 are the railroad switches that are laid on reinforced concrete bars, of type R65, brands 1/11 and 1/9, designed by PTKB CP MPS – 1740 and 2215 [1]. At present, these basic models of railroad switches are significantly modified. The modifications were introduced to separate structural units while maintaining basic geometric dimensions [2, 3]. There are many pilot designs of railroad switches currently in operation that are based on new structural solutions. These include the introduction of oblique connection, extending rail endings and the implementation of an impact-free rolling surface on the frog [4].

The processing of statistical data on the total weight of the passed cargo revealed that the current profile based on GOST 28370-89 does not meet operational conditions because the average time of a frog life cycle along all the examined routes of Ukrzaliznytsia does not reach a warranted time of operation [3]. In most cases, a frog life cycle is almost twice shorter in terms of failure-free operation.

Analysis of the investigated frogs against the total weight of the passed cargo showed that the largest percentage of frog failures is due to chipping and wear of the core of frogs and rail wings. If one analyzes the distribution of defects among the most common designs of railroad switches, one can see that the largest number of failures in frogs is observed for the 1740 design (Fig. 1).

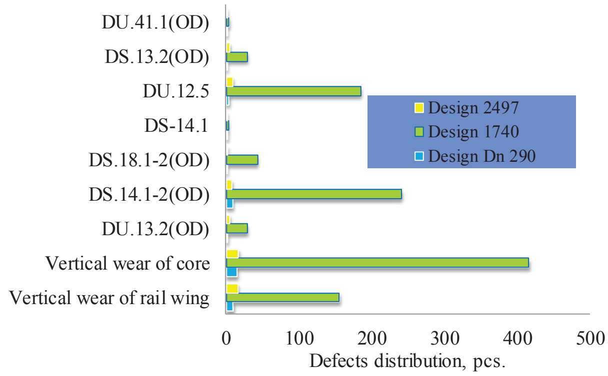

Fig. 1. Defect distribution histogram for the designs of railroad switches

Studies into the features of interaction between a track and rolling stock in the zone of railroad switches have found [5, 6] that a vertical irregularity in the zone of the rolling surface of a railroad switch [7] creates additional dynamic forces of rolling stock on the frog.

To determine dynamic forces of interaction on the frogs mounted on reinforced concrete base, it is necessary, first of all, to establish the types and parameters of vertical irregularities of frogs at different levels of wear.

There is a known device for measuring the wear of the core and rail wings of frogs [9], A. K. Yankovskiy ruler, which has a horizontal steel bar with a marked millimeter scale, movable and fixed supports. The disadvantage of measurement is significant labor intensity as one displacement of the ruler enables to obtain only one value of wear of the core or a rail wing of the frog. In addition, human factor manifests itself in the influence on the measuring results that depend on the proper position of the ruler and a reference point.

A mechanical crossing-piece profilographer, known in Russia (patent RU No. 89120), designed to measure the cross-sectional profile of frogs, does not make it possible to map a profile image onto paper at atmospheric precipitation; it also has a limited scope of application because its operation is based on the mechanical principle of action. Additional disadvantages of the profilographer include the limited measurement of a frog profile only in longitudinal direction, dependence of results on the transversal position of the measuring wheel and its profile, as well as the necessity to change the profile of a measuring wheel in order to measure the motion trajectory of wheels with metal wear on the rolling surface.

At present, many mechanical and inertial systems are used for the diagnosis of railroad switches in the countries of the European Union [3]. These systems are aimed at measuring the parameters of dynamic interaction between frogs when railroad rolling stock passes over them. The most widely used at the EU railroads is the mechanical profilographer Miniprof-Switch for measuring the transverse profile of a frog core (Fig. 2). However, the system makes it possible to obtain a cross profile of the frog only at a particular intersection of the core, rather than the surface along the core, which does not allow the objective evaluation of technical condition of the crossing.

Fig. 2. Crossing profilographer Miniprof-Switch

In Germany, the diagnosis of frogs is performed using the system ESAH-M and ESAH-F. The system ESAH-M (Fig. 3) is a device for recording accelerations and a device for determining motion speed of the rolling stock.

Fig. 3. Inertial system for diagnosing the frogs of rail switches ESAH-M

The measurements of accelerations in the frog core, performed over many years, showed that this system yields a considerable variation in the measured values of accelerations. This is due primarily to disregarding the factors that arise during interaction between a wheel of the rolling stock and the frog: taking into consideration a motion direction of the rolling stock, identification of place of the impact, which has a significant influence on the value of accelerations.

The known system for diagnosing the frogs of railroad switches ESAH-F (Fig. 4), which consists of an acceleration sensor and a data collection system, located on a rail vehicle, a speed meter, and a navigation device, estimates threshold values of the measured vibration accelerations. In the case when the assigned limiting values of vibration accelerations are exceeded, further thorough control measurements of the state of the elements of the switch, intersection, or frog, are performed. As a result, it becomes possible to predict the time required for repairs, as well as related expenses for maintenance.

Fig. 4. Inertial system for diagnosing the frogs of railroad switches ESAH-F

However, when a rail vehicle passes over a railroad switch, a frog, a turnout, or a rail junction, it is impossible to determine their actual wear to such an accuracy that it would be possible, even in the absence of a damaged condition, to predict the required type of repair work. It is possible only to establish that, as a result of exceeding a certain threshold value, the respective section of a track has already been damaged. In addition, it is impossible, while using a given device, to determine technical condition of all the frogs at a railroad station due to a large amount of information collected along the section of train motion, and the difficulty of identification of operational crossings.

Therefore, designing measurement systems for parameters of geometric irregularities arising at frogs of railroad switches would make it possible to predict their life cycle. The monitoring of vertical wear of frogs that should be performed would make it possible to take timely engineering decisions for improving the carrying capacity of frogs in railroad switches.

2. Literature review and problem statement

The main factor that affects the level of dynamic forces on frogs is the irregularity in vertical plane, which is caused by the profile of rail wings and the core [8, 9]. As a result, the longitudinal and transverse profiles of a frog affect intensity of the elements wear, formation of defects, and ultimately its operation cycle.

In paper [10], authors established that the most common are the irregularities of a sinusoidal shape, as well as hollows and hills. The most unfavorable in terms of force interaction are the irregularities in the form of cavities and the sinusoidal ones [11].

The greatest interaction forces are implemented along the sections of an irregularity in the region of wheel advance on the slope of an opposite direction [12].

It was proven in paper [13] that the vertical motion trajectory of the center of a new wheel, when rolling over an irregularity, is almost completely identical to the vertical irregularity itself at the frog rolling surface. Thus, a vertical rolling trajectory of the unworn wheel characterizes a vertical irregularity at a frog. Based on this dependence, a design of the measuring device, a trajectory tracker, was proposed to record the real shape of irregularities at the frogs.

A large amount of experimental research into wheel rolling trajectories over frogs of different designs and brands of railroad switches for both main line and industrial transport were reported in [8, 9].

The authors of these papers obtained average irregularities that characterize frogs of railroad switches of different design in the condition of medium wear and permissible maximum wear. In addition, they considered train motion directions (forward motion (FD), or backward motion (BW)). For the average irregularities, each ordinate equals a mathematical expectation of the irregularity's ordinate at a given point, in the processed number of irregularities at frogs of a particular design, type and brand.

It should be noted that almost all previous studies were carried out for railroad switches laid on wooden bars. The research into determining the dependence of forces of interaction on parameters of the vertical irregularities at frogs for switches laid on reinforced concrete bars started only 10–15 years ago.

Specifically, in the early 90-ies, author of work [14] obtained first characteristic trajectories for frogs laid on the reinforced concrete bars. The author, however, did not conduct analysis of dependence of the shape of an irregularity on the period of operation and prevailing direction of trains motion. The given trajectories have the shape of asymmetrical sinusoids, which do not accurately enough reflect the actual outline of irregularities, which could directly affect the analysis of magnitudes of interaction forces.

A more thorough study into irregularities at railroad switches, laid on reinforced concrete bars, was conducted in the mid 1990's–2005, initially at DIIT (on the Pridneprovska railroad) [15], and later at DETUT (on the South Western Railroad) [16].

However, the established dependences of the vertical wear of frogs on the total weight of goods that have passed the railway are not applicable either for contemporary designs of railroad switches, or modern operational conditions. Given the current designs of railroad switches on reinforced concrete bars, it is necessary to conduct additional research into formation of vertical irregularities depending on the total weight of the passed cargo and the motion speed of rolling stock.

In paper [15], author measured about forty irregularities at frogs of type P65, brand 1/11, laid on reinforced concrete bars. In this case, the author points to the existence of differences between irregularities at the frogs, mounted on reinforced concrete bars and wooden bars. In addition, the author established characteristic shapes and parameters of irregularities taking into consideration the prevailing motion direction and total weight of the passed cargo. However, the author does not give recommendations for predicting the formation of vertical irregularities at a frog depending on the operating conditions.

In paper [16], based on data from field measurements (more than 130 trajectories), author established the average vertical irregularities at the rolling surface of frog of the type P65, brand 1/11, laid on reinforced concrete bars. It was found that vertical irregularities on the rolling surface of frogs, mounted on reinforced bars, and the corresponding irregularities at frogs laid on wooden bars, differ significantly both in shape and basic parameters. Specifically, it was established that the irregularities at frogs, laid on reinforced concrete bars, are more local in character and have a smaller length with steeper slopes. Countercurrent slopes i_z are 1.2 times larger, and total slopes Σi are 1.6 times larger, at forward motion, and, respectively, are 1.17 and 1.03 times greater during backward movement of trains. However, a given work fails to resolve the issue of forming the wear and irregularities at the rolling surface of railroad switches on reinforced concrete bars and their impact on the vertical dynamics of interaction between a track and rolling stock. Another open question is the formation of irregularities over the initial period of frog operation when a metal is exposed to a bearing stress, which significantly affects the formation of a vertical irregularity.

Summing up the above, one should note that the volume of research into irregularities at railroad switches, laid on reinforced concrete bars, is, up to now, much less than the corresponding amount of research concerning the wooden bars. It should be emphasized that at present the reinforced concrete bars are the main type of under-rail base both at the railroads of Ukraine and on most railroads in the world. In addition, it should be noted that practical research actually lacks measurement results for irregularities at frogs of railroad switches of brand 1/9, laid on reinforced concrete bars. These particular railroad switches, along with those of brand 1/11, are the most common in the network of Ukrainian railroads.

Furthermore, the recent years have seen the emergence of a number of new designs of frogs whose working patterns under operational loads also require a comprehensive study. Therefore, research into the specified field is necessary in order to ensure the safety of train motion over the railroad switches and in order to improve their average life cycle.

3. The aim and objectives of the study

The aim of present study is the experimental estimation of condition of the longitudinal profile of frogs at railroad switches and the construction of a mathematical model for predicting the patterns in the development of irregularities at the rolling surfaces of rail wings and the core of a frog.

To accomplish the aim, the following tasks have been set:

– to devise an innovative system for measuring the longitudinal profile of frogs at railroad switches;

– to conduct experimental measurements of the longitudinal profile of frogs at different values of the total weight of passed cargo;

– to develop a procedure for determining the trajectory of motion of the center of mass of a wheel over a frog;

– to build a mathematical model for predicting the wear of frogs depending on the total weight of passed cargo.

4. Design of the device for measuring the longitudinal profile of frogs

In order to measure and control the longitudinal profile of frogs, we have designed a device – the frog profilographer [17]. It is composed of a frame with left and right racks, lateral supports, a rectangular frame with an upper horizontal rod, a head that can move along a horizontal rod (Fig. 5, 6). When performing measurements, the developed software instructs personal computer (1) through programmable microcontroller (2) to start measuring. The microcontroller activates stepper motor (3) and shifts, along a horizontal guiding rod, laser (5) and photo camera (6) at a preset distance. This results in taking images of the profile at a certain step in the motion of the camera and the laser. The photo camera registers graphical image of the laser plane crossing the surface of the frog. By using the developed algorithms of automatic recognition and measurement of bitmap images, we determine parameters of the measured crossing of the frog surface. At a sufficient accuracy of measurement, the developed software instructs a personal computer to measure the intersection of a frog surface at the following step of moving the measuring system. Upon execution of measurements of the transverse profile of frog surface for the preset number of steps of the longitudinal motion of the measuring system, the results of separate measurements are merged to form a mathematical model of the frog surface. To activate operation of the laser, we use power supply unit (7), which is powered by means of the developed autonomous power supply system [18].

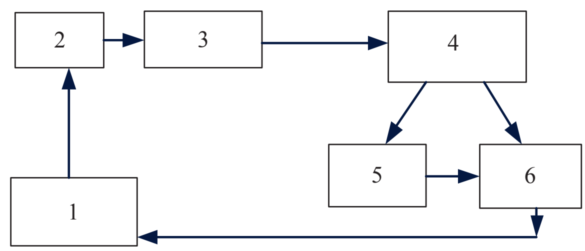

Fig. 5. Block diagram of measurements of the profile (surface) of frogs

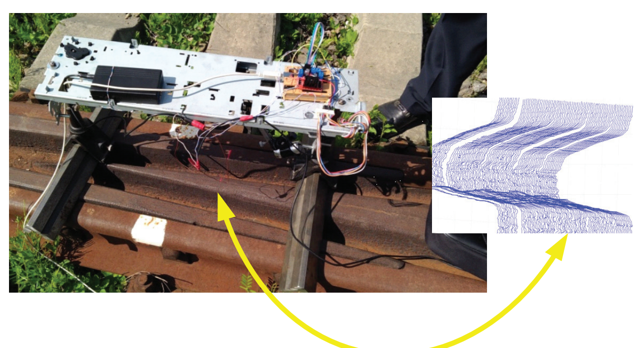

Fig. 6. Practical measuring of the profile (surface) of frogs at fifty points

The developed device measures the profile of frogs using a high-resolution photo camera and a laser plane. The result of the measurements is the spatial arrangement of points of the frog surface. Since the filming of the cross-sectional profile of the frog is carried out in a controlled fashion employing a programmed microcontroller, which, using the software developed, controls the stepper motor, and shifts, along a horizontal guiding rod, the laser and the photo camera at a set distance, then it is possible to obtain the profile of a frog of any brand by changing only the length of the movement of the laser and the camera. In this case, the accuracy of measurements of the cross-sectional profile will not change.

Based on the results of measurements of profiles of frogs at railroad switches, it is possible to make scientifically-substantiated decisions regarding the need for recovery repair of frogs.

Frog profilographer could be used for measuring the vertical wear of frogs of type P65, brands 1/18, 1/11, and others.

5. Results of experimental measurements of the profile of frogs at the railroads of Ukraine

Full scale measurements of the longitudinal profile of frogs based on GOST 28370-89 were conducted for frogs of brand 1/11, type P65, laid on the reinforced concrete bars. The number of measured frogs is 50 pcs. The measurements were conducted along both direct and lateral directions. Based on these measurements, we constructed average profiles of frogs. Changes in the longitudinal profile after passing 50–65 million tons of cargo are shown in Fig. 7; and after passing 80–95 million tons – in Fig. 8. In these figures, blue color indicates motion in the direct direction of the frog, yellow color denotes lateral direction, and orange color – over the core.

Fig. 7. Average longitudinal profile of frog, brand 1/11, after passing 50–65 million tons of cargo

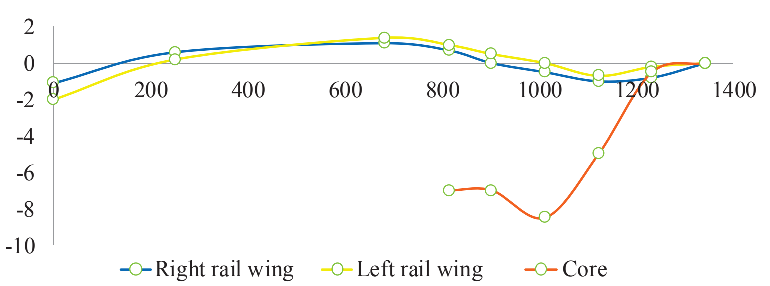

Fig. 8. Average longitudinal profile of frog, brand 1/11, after passing 80–95 million tons of cargo

We can conclude based on the above diagrams that the core of a frog undergoes the most intense wear. Measurements have shown that 60 % of frogs at a cross-section of 20 mm have a core height between – 2.1 and 6.1 mm relative to the head of rail wings against the standard of 1.5 mm and – 0.5 mm. The most rapidly worn out are the cores at cross-section from 12 mm to 30 mm. The slopes of the profile of rail wings from the lead to the mathematical center point of a frog become more flat when the magnitude of total weight of the passed cargo increases as compared to those at average degree of the passed cargo.

To analyze a change in the irregularity depending on the passed cargo, we split all irregularities into several groups. The division into groups was conducted so that one group would include the rail switches with a difference in the passed cargo not exceeding 15 million tons.

To select characteristic irregularities at average and maximal permissible degrees of wear, experimental material was grouped into two large groups (50–65 million tons, and 80–95 million tons).

6. Procedure for determining the trajectory of motion over frogs at railroad switches

Two techniques are currently employed to determine a trajectory: graphical and analytical.

Graphical method is based on the use of a specialized device, trajectory tracker, whose application is described in papers [6, 19].

In the present work, we employed an analytical method for determining the trajectory of wheel motion over a frog [3]. Based on a given method, we established the dependence between the influential parameters and the initial trajectory of wheel motion over a frog.

A wheel, regardless of the distance traveled, is modeled based on one width of the bandage of the wheel. The base for determining vertical coordinates of the wheel diameter is the wheel rotation axis. Determining an irregularity comes down to determining function $y(x)$ [20–22]. At nodes, the function must accept values that correspond to the location of the center of the wheel in a vertical plane relative to the location of the center of the wheel, calculated for the first point.

To do this, we define in a unified coordinate system for the models of a wheel and a frog coordinates of the frog diameter and the wheel diameter. A point of contact of the wheel and the frog at a specific diameter is in the place where the difference of applicates in a transversal profile of the wheel and the frog diameter is the smallest. The resulting difference is the distance that is needed by the wheel to come down prior to the contact with the frog. In order to determine the irregularity, it is necessary to subtract the distances obtained from the corresponding distance at the beginning of the irregularity.

In a general form, a trajectory of wheel motion over a frog can be written in the form of dependence:

$$y(x)=f\{\Pi(x),W(x),\delta\}, \tag{1}$$

where $y(x)$ is the trajectory of wheel that rolls over a frog in the vertical plane; $P(x)$ is the profile of the frog; $W(x)$ is the transverse profile of the wheel bandage; δ is the magnitude of the gap between a working edge of the wheel and a working edge of the rail wing (core).

The profile of a frog is considered to be the longitudinal profile of the rolling surface of rail wings and core. The longitudinal profile of the frog will be represented in the form of two linear functions: $P_w(x)$ is the longitudinal profile of the rail wings, and $P_c(x)$ is the longitudinal profile of the core.

Fig. 9 shows abscissas of functions $P_w(x)$ and $P_c(x)$, which were accepted for the calculation of a frog, brand 1/11.

The rolling trajectory of the center of mass of the wheel over the frog is significantly affected by the magnitude of deviation of rail wings in plan $y(x)$, which is determined by the structural dimensions of the frog (Fig. 10).

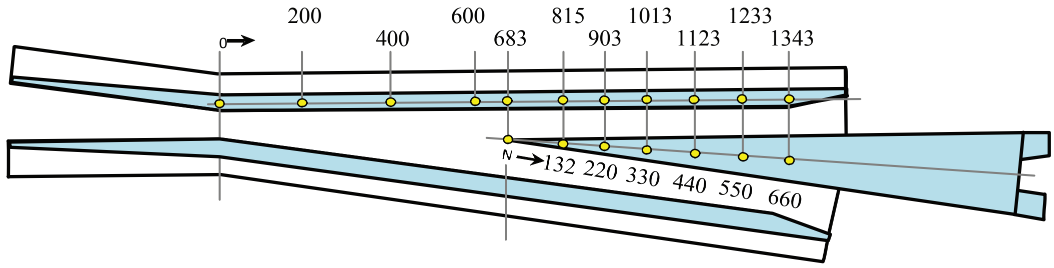

Fig. 9. Longitudinal profile of a frog, brand 1/11

For a frog of brand 1/11, deviation of the rail wing is calculated from formulae:

$$z(x)=0.067x \text{ at } 0<x<683, \quad (2)$$

$$z(x)=45+0.0909x \text{ at } 683<x<1068. \quad (3)$$

The transverse profile of the wheel bandage is given in the form of function $W(x)$. This function shows a change in the profile of a wheel depending on the magnitude of its rolling (Fig. 11).

In this case, the magnitude of wheel roll and, accordingly, the transverse profile of the wheel bandage, is a random magnitude. The curve of probability distribution of the magnitude of wheel roll, which was built based on the mass measurement of wheelsets, is given in paper [5]. Mathematical expectation for the magnitude of wheel roll $W=0.83$ mm, mean square deviation $\sigma=1.54$ % mm. The average characteristics of the wear of wheel are given in Table 1.

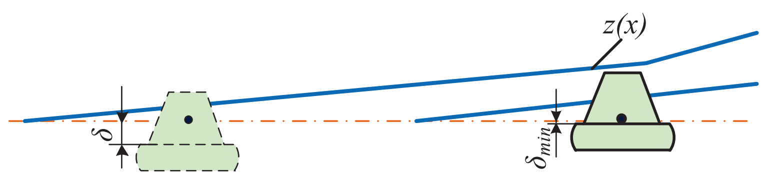

Fig. 10. Schematic of wheel motion over a frog in plan

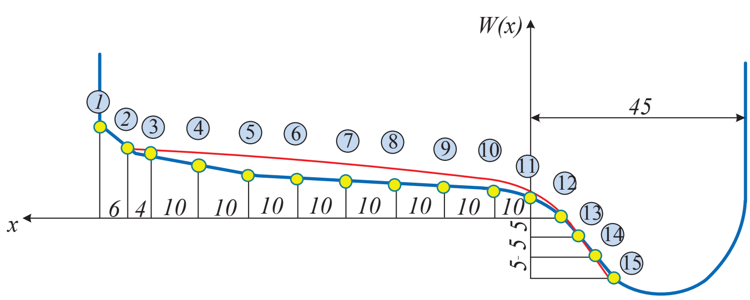

Fig. 11. Representation of the transverse profile of the wheel bandage

Thus, we have all initial data for determining the vertical trajectory of wheel motion over a frog. Calculation of the trajectory will be performed using the following dependences:

$$z(x)=\Pi_B(x)-W\{y(x)+\delta\} \text{ at } x<x', \quad (4)$$

$$z(x)=\Pi_C(x)-W\{\delta\} \text{ at } x>x', \quad (5)$$

where x' is the abscissa of the point of transition of a wheel from the rail wing to the core.

Results of the obtained average trajectories of motion over frogs of brands 1/11 depending on the passed cargo are shown in Fig. 12, Fig. 13.

Fig. 12, 13 show that after passing 50–65 million tons (that corresponds to the average degree of wear), the trajectory has the shape of a bump. We observe on the reinforced concrete base in the zone when a wheel rolls from a rail wing onto the core sharp hollows, characterized by significant total inclination. Subsequently, when the passed cargo increases, the number of sinusoidal irregularities grows. At a wear close to maximal (80–95 million tons passed), the percentage of unfavorable trajectories (sinusoidal and hollows) increases. At low wear, they make up 49.8 %, at a wear of 5–6 mm and larger – 88.3 %. Sometimes there is a transformation of the sinusoidal irregularities to the wave-shaped ones.

A hollow in the irregularity increases in size when the passed cargo grows (this explains the transition from an irregularity in the shape of a bump to the sinusoidal one); in this case, the depth of the irregularity increases while the height of the bump decreases.

Depth of an irregularity varies slightly (2–4 mm after passing 50–65 million tons and 5–6 mm when passing 80–95 million tons).

Maximum slope often decreases with an increase in the passed cargo; irregularities become flatter.

Table 1

Characteristics of a medium worn wheel

Statistical characteristics of wheel wear	Number of the wheel profile cross-section														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mean value of roll W, mm	0.83	1.44	2.57	2.72	2.72	2.68	2.38	1.66	1.17	0.87	0.87	1.51	1.49	0.74	0.43
Standard deviation, σ	1.54	1.74	2.04	2.06	2.02	2.01	1.90	1.64	1.47	1.42	1.19	1.39	1.08	1.03	0.90

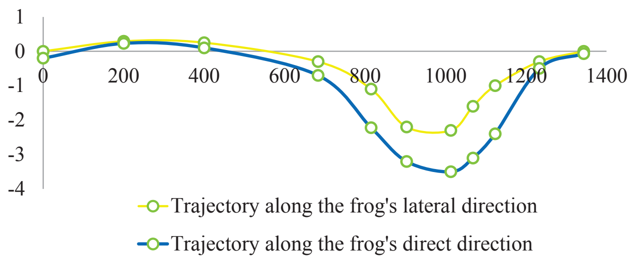

Fig. 12. Average trajectories of motion along actual longitudinal profiles of frogs, brand 1/11, after passing 50–65 million tons

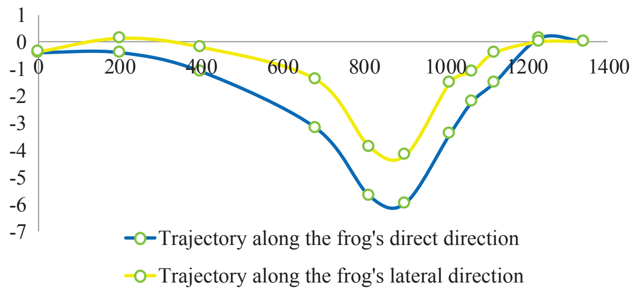

Fig. 13. Average trajectories of motion along actual longitudinal profiles of frog, brand 1/11, after passing 80–95 million tons

7. Mathematical model of motion trajectory over a frog

Assume that at points $x=x_1$, $x=x_2$,..., $x=x_n$ the function by means of which we determine the trajectory of wheel motion over a frog takes values y_1, y_2 ..., y_n. We shall build a polynomial regression equation for magnitudes y_i on magnitudes x_i. This equation is given in the form:

$$Y_i = a_0 + a_1 x_i + a_2 x_i^2 + \ldots + a_6 x_i^6. \qquad (6)$$

Parameters a_j $(j=0,1,...,6)$ will be derived by the least square method, according to which the sum of the squares of deviations $Y_i - y_i$ should be minimal. This sum is a function:

$$F(a_0, a_1, ..., a_6) = \sum_{i=1}^{n} \left(a_0 + a_1 x_i + a_2 x_i^2 + \ldots + a_6 x_i^6 - y_i\right)^2. \qquad (7)$$

Then partial derivatives will be written in the form of a system of equations:

$$\begin{aligned}
\frac{\partial F}{\partial a_0} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} = 0,\\
\frac{\partial F}{\partial a_1} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} x_i = 0,\\
\frac{\partial F}{\partial a_2} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} x_i^2 = 0,\\
\frac{\partial F}{\partial a_3} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} x_i^3 = 0,\\
\frac{\partial F}{\partial a_4} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} x_i^4 = 0,\\
\frac{\partial F}{\partial a_5} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} x_i^5 = 0,\\
\frac{\partial F}{\partial a_6} &= 2\sum_{i=1}^{n}\begin{pmatrix} a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \\ + a_4 x_i^4 + a_5 x_i^5 + a_6 x_i^6 - y_i \end{pmatrix} x_i^6 = 0.
\end{aligned} \qquad (8)$$

By equating to zero partial derivatives $\partial F/\partial a_0$, $\partial F/\partial a_1$, ..., $\partial F/\partial a_6$ and by performing basic transforms, we shall obtain a system of linear equations for determining x_0, x_1,..., x_6:

$$\begin{aligned}
& n a_0 + \left(\sum_{i=1}^{n} x_i\right) a_1 + \left(\sum_{i=1}^{n} x_i^2\right) a_2 + \left(\sum_{i=1}^{n} x_i^3\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^4\right) a_4 + \left(\sum_{i=1}^{n} x_i^5\right) a_5 + \left(\sum_{i=1}^{n} x_i^6\right) a_6 = \sum_{i=1}^{n} y_i,\\
& \left(\sum_{i=1}^{n} x_i\right) a_0 + \left(\sum_{i=1}^{n} x_i^2\right) a_1 + \left(\sum_{i=1}^{n} x_i^3\right) a_2 + \left(\sum_{i=1}^{n} x_i^4\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^5\right) a_4 + \left(\sum_{i=1}^{n} x_i^6\right) a_5 + \left(\sum_{i=1}^{n} x_i^7\right) a_6 = \sum_{i=1}^{n} x_i y_i,\\
& \left(\sum_{i=1}^{n} x_i^2\right) a_0 + \left(\sum_{i=1}^{n} x_i^3\right) a_1 + \left(\sum_{i=1}^{n} x_i^4\right) a_2 + \left(\sum_{i=1}^{n} x_i^5\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^6\right) a_4 + \left(\sum_{i=1}^{n} x_i^7\right) a_5 + \left(\sum_{i=1}^{n} x_i^8\right) a_6 = \sum_{i=1}^{n} x_i^2 y_i,\\
& \left(\sum_{i=1}^{n} x_i^3\right) a_0 + \left(\sum_{i=1}^{n} x_i^4\right) a_1 + \left(\sum_{i=1}^{n} x_i^5\right) a_2 + \left(\sum_{i=1}^{n} x_i^6\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^7\right) a_4 + \left(\sum_{i=1}^{n} x_i^8\right) a_5 + \left(\sum_{i=1}^{n} x_i^9\right) a_6 = \sum_{i=1}^{n} x_i^3 y_i,\\
& \left(\sum_{i=1}^{n} x_i^4\right) a_0 + \left(\sum_{i=1}^{n} x_i^5\right) a_1 + \left(\sum_{i=1}^{n} x_i^6\right) a_2 + \left(\sum_{i=1}^{n} x_i^7\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^8\right) a_4 + \left(\sum_{i=1}^{n} x_i^9\right) a_5 + \left(\sum_{i=1}^{n} x_i^{10}\right) a_6 = \sum_{i=1}^{n} x_i^4 y_i,\\
& \left(\sum_{i=1}^{n} x_i^5\right) a_0 + \left(\sum_{i=1}^{n} x_i^6\right) a_1 + \left(\sum_{i=1}^{n} x_i^7\right) a_2 + \left(\sum_{i=1}^{n} x_i^8\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^9\right) a_4 + \left(\sum_{i=1}^{n} x_i^{10}\right) a_5 + \left(\sum_{i=1}^{n} x_i^{11}\right) a_6 = \sum_{i=1}^{n} x_i^5 y_i,\\
& \left(\sum_{i=1}^{n} x_i^6\right) a_0 + \left(\sum_{i=1}^{n} x_i^7\right) a_1 + \left(\sum_{i=1}^{n} x_i^8\right) a_2 + \left(\sum_{i=1}^{n} x_i^9\right) a_3 + \\
& + \left(\sum_{i=1}^{n} x_i^{10}\right) a_4 + \left(\sum_{i=1}^{n} x_i^{11}\right) a_5 + \left(\sum_{i=1}^{n} x_i^{12}\right) a_6 = \sum_{i=1}^{n} x_i^6 y_i.
\end{aligned} \qquad (9)$$

Results of mathematical modeling of the motion trajectory of the center of mass of the wheel over a frog are shown in Fig. 14, 15.

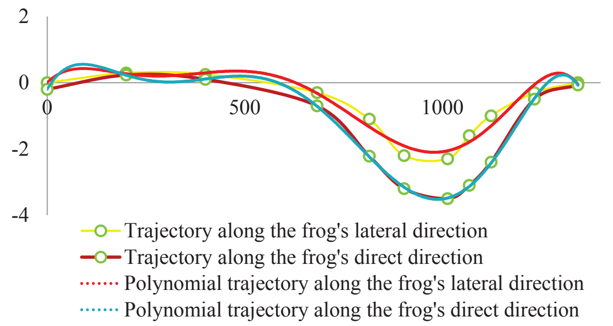

Fig. 14. Mathematical interpretation of motion trajectories by the polynomial function after the frog passed 50–65 million tons of cargo

The coefficients of a polynomial, by using which we determine the average motion trajectory of a wheel along the longitudinal profiles of frogs, brand 1/11, after passing 50–65 million tons, take, for a lateral motion direction, the following values: $a_0=0.0039$, $a_1=0.0116$, $a_2=-0.0001$, $a_3=4\cdot10^{-7}$, $a_4=-6\cdot10^{-10}$, $a_5=5\cdot10^{-13}$, $a_6=-1\cdot10^{-16}$, and, for a direct motion direction: $a_0=-0.1993$, $a_1=0.0207$, $a_2=-0.0002$, $a_3=7\cdot10^{-7}$, $a_4=-1\cdot10^{-9}$, $a_5=8\cdot10^{-13}$ and $a_6=-2\cdot10^{-16}$.

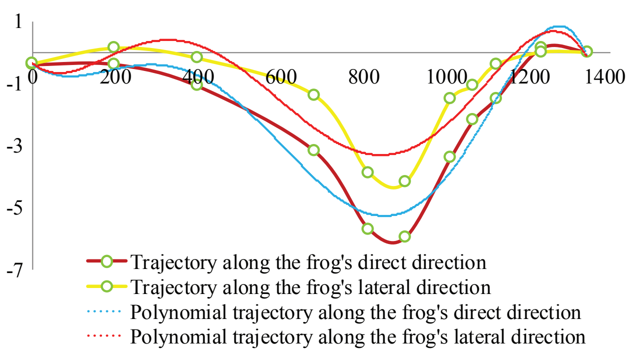

Fig. 15. Mathematical interpretation of motion trajectories |by the polynomial function after the frog passed 80–95 million tons of cargo

The coefficients of a polynomial, by using which we determine the average motion trajectory of a wheel along the longitudinal profiles of frogs, brand 1/11, after passing 80–95 million tons, take, for a lateral motion direction, the following values: $a_0=-0.3422$, $a_1=-0.0115$, $a_2=0.0001$, $a_3=-3\cdot10^{-7}$, $a_4=4\cdot10^{-10}$, $a_5=-1\cdot10^{-13}$, $a_6=1\cdot10^{-17}$, and, for a direct motion direction: $a_0=-0.377$, $a_1=-0.0102$, $a_2=8\cdot10^{-5}$, $a_3=-2\cdot10^{-7}$, $a_4=1\cdot10^{-10}$, $a_5=5\cdot10^{-14}$ and $a_6=-4\cdot10^{-17}$.

8. Discussion of research results aimed at estimating the condition of frogs at railroad switches

The proposed system for diagnosing the frogs of railroad switches, based on the usage of modern microcontrollers of the type ESP, along with the joint application of the information technology IoT (Internet of Things), has advantages over mechanical systems in terms of the accuracy of data acquired, their operational processing and sending to user in order to analyze technical condition of the frogs at railroad switches. The results of measuring the transverse profile of frogs at railroad switches make it possible to take scientifically-substantiated decisions regarding the need for recovery repair of frogs by the method of surfacing and for control over gradual decrease in their carrying capacity, for establishing their actual technical condition and residual resource.

By conducting high-precision measurements of the cross-sectional profile of frogs at railroad switches employing the proposed system, it was established that upon passing of 50–65 million tons (that corresponds to the average degree of wear) the trajectory has the shape of a bump. We observed, at the reinforced concrete base in the zone where a wheel rolls from a rail wing onto the core, sharp hollows, characterized by a significant total inclination. Subsequently, when the passed cargo increases, the number of sinusoidal irregularities grows. At wear close to maximal (80–95 million tons passed), the percentage of unfavorable trajectories (sinusoidal and hollows) grows. At low wear, they make up 49.8 %, at a wear of 5–6 mm and larger – 88.3 %. Sometimes there is a transformation of the sinusoidal irregularities into the wave-shaped ones. The number of irregularities obtained (especially for small and medium passed cargo) does not allow us to make conclusions based on the laws of probability theory and mathematical statistics. Therefore, during analysis, we considered a totality of separate irregularities in a group, and, based on this, we drew conclusions about the patterns of development.

Research into force interaction of rolling stock over frogs at railroad switches must be conducted taking into consideration parameters of vertical irregularities. They in turn depend on the technical and structural parameters of frogs and wheels of rolling stock.

Thus, in order to solve the problems on determining dynamic forces of interaction over frogs laid on the reinforced concrete base, it is necessary first to establish the types and parameters of vertical irregularities of such frogs at different levels of wear.

In order to predict the wear of frogs at railroad switches, it is necessary to continue to measure the cross-sectional profile of frogs in the modern promising designs of railroad switches, such as Dn 290, Dn 345, which would make it possible to establish the types of vertical irregularities and their geometric parameters depending on the total weight of passed cargo.

One of the drawbacks of the proposed system is the impossibility of conducting measurements in the presence of snow cover over a frog, which affects results of the measurements. It should also be noted that this work reports results of studies into vertical irregularities of frogs of brand 1/11 only. Therefore, research in the future, in order to develop criteria for the reliability and functional safety of railroad switches, should estimate the degree of wear for frogs of various types and brands.

9. Conclusions

1. Applying the proposed system for diagnosing the frogs of railroad switches, it is possible to prevent the premature frog failure and thus to provide the safety of trains. A given system for diagnosis is based on using modern microcontrollers of the type ESP with high technical characteristics and

the simultaneous application of the information technology IoT (Internet of Things). Measurement of parameters of the transverse profile of a frog will be based on programmable microcontrollers of the type ESP. In addition, the system performs preprocessing of data collected and their submission in a user-friendly format, as well as saving them, in order to ensure the long-term monitoring of frogs at railroad switches.

The results of measuring the transverse profile of frogs at railroad switches make it possible to take scientifically-substantiated decisions regarding the need for recovery repair of frogs by the method of surfacing and for control over gradual decrease in their carrying capacity, for establishing their actual technical condition and residual resource.

2. The results of experimental data allowed us to establish that basic parameters, which characterize an irregularity at the frog rolling surface, are the shape, depth and inclination of a given irregularity. When a frog passes more than 50 million tons of cargo, the basic form of an irregularity at the frog changes insignificantly, with changes occurring mostly to the depth, as well as slopes of an irregularity that characterize the steepness.

3. Coefficients of polynomial of the seventh degree, by using which we determine the average motion trajectory of a wheel along the longitudinal profiles of frogs, brand 1/11, after passing 50–65 million tons, take, for a lateral motion direction, the following values: $a_0=0.0039$, $a_1=0.0116$, $a_2=-0.0001$, $a_3=4\cdot10^{-7}$, $a_4=-6\cdot10^{-10}$, $a_5=5\cdot10^{-13}$, $a_6=-1\cdot10^{-16}$, and, for a direct motion direction: $a_0=-0.1993$, $a_1=0.0207$, $a_2=-0.0002$, $a_3=7\cdot10^{-7}$, $a_4=-1\cdot10^{-9}$, $a_5=8\cdot10^{-13}$, $a_6=-2\cdot10^{-16}$. After passing 80–95 million tons, coefficients of polynomial of the seventh degree take, for a lateral motion direction, the following values: $a_0=-0.3422$, $a_1=-0.0115$, $a_2=0.0001$, $a_3=-3\cdot10^{-7}$, $a_4=4\cdot10^{-10}$, $a_5=-1\cdot10^{-13}$, $a_6=1\cdot10^{-17}$; and, for a direct motion direction: $a_0=-0.377$, $a_1=-0.0102$, $a_2=8\cdot10^{-5}$, $a_3=-2\cdot10^{-7}$, $a_4=1\cdot10^{-10}$, $a_5=5\cdot10^{-14}$, $a_6=-4\cdot10^{-17}$. The selected polynomial of the seventh degree most accurately describes the vertical motion trajectory of the center of mass of the wheel over a frog of the railroad switch.

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MINIMIZING THE MASS OF A FLAT BOTTOM OF CYLINDRICAL APPARATUS

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Отримано загальний розв'язок задач згину круглих пластин, товщина яких змінюється за експоненціальним законом із застосуванням вироджених гіпергеометричних функцій Куммера. Розв'язано задачу контакту циліндричної оболонки з круговою пластиною змінної товщини в загальному вигляді. Запропоновано методику мінімізації маси пластинчастих елементів конструкцій кругової форми. Розроблена конструкція зони переходу від днища до стінки, міцність якої перевірена методом скінчених елементів у реальному проектуванні

Ключові слова: днище змінної товщини, гіпергеометрична функція Куммера, контакт оболонки та кругової пластини

Получено общее решение задач изгиба круглых пластин, толщина которых меняется по экспоненциальному закону с применением вырожденных гипергеометрических функций Куммера. Решена задача контакта цилиндрической оболочки с круговой пластиной переменной толщины в общем виде. Предложена методика минимизации массы пластинчатых элементов конструкций круговой формы. Разработана конструкция зоны перехода от днища к стенке, прочность которой проверена методом конечных элементов в реальном проектировании

Ключевые слова: днище переменной толщины, гипергеометрическая функция Куммера, контакт оболочки и круговой пластины

1. Introduction

The main tasks in the design of machinery and vehicles imply achieving the highest technical-economical and operational indicators: performance, operational reliability, and cost. One of the most important factors when solving these tasks is the minimization of mass of structures. The greatest attention to the problem of reducing the mass is paid in transport engineering. Thus, the thickness of passenger cars made by different manufacturers is 1...2 mm; the thickness of the unloaded sections of modern automotive bodies (wing, trunk, etc.) does not exceed 0.7 mm, in some makes – 0.3 mm. The trend of decreasing thickness is limited mainly by the possibilities of manufacturing high-quality thin-walled rolled metal.

In transport engineering, one of the main criteria of quality is the ratio g_1 of payload mass to the mass of the structure. For marine transport, g_1=2.3...7.0; for railroad transport, g_1=2.0...2.5; for automobile transport, g_1=0.5...1.5, for aviation, g_1=0.3...0.75. The larger magnitudes here correspond to the largest size of vehicles. Similar characteristics are calculated for stationary machines and apparatuses. These data explain the steady trend of growth in the dimensions of machinery and technological equipment.