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The Mathematical Support of Machine Surfacing for the Railway Track

D. Kurhan[1,*], M. Havrylov[2]

[1] Dnipro National University of Railway Transport named after Academician V. Lazaryan, Department of Track and Track Facilities
Lazaryan st. 2, 49010, Dnipro, Ukraine
***E-mail: kurhan.d@gmail.com**

[2]Dnipro National University of Railway Transport named after Academician V. Lazaryan, Department of Roads Design and Construction
Lazaryan st. 2, 49010, Dnipro, Ukraine

Abstract: The condition of a railway track is characterized by many indices, including its geometric shape, both in the horizontal and vertical planes. The purpose of this paper is to create a mathematical tool to ensure the operation of track machines for surfacing, tamping, and alignment, which are equipped with automation systems. The developed mathematical model will be integrated into the AS "Strela" software package which is currently installed on machines. Scientific approaches used in the mathematical model allowed to reduce the operation of machines in "window", to simplify the work of maintenance personnel, to create an information base of track parameters, to establish rational parameters of curves during surfacing.

Keywords: railway; surfacing; track survey; chord method; track maintenance

1. Introduction

One of the tasks in the organization of railway transport operation was and remains the task of maintaining the railway track in a state consistent with the relevant regulatory documents from the viewpoint of ensuring the safe passage of rolling stock with prescribed speeds. The condition of a railway track is characterized by many indices, including its geometric shape, both in the horizontal and vertical planes. Even the perfect installation of the permanent way during the overhaul does not ensure the preservation of its position over time. The force of rolling stock, natural and other factors lead to the need for intermediate repairs to eliminate deviations in the track geometry, which are out-of-tolerance. This requires solving the following tasks:

- to obtain information concerning the condition of the railway track in space with sufficient accuracy;
- while engineering to receive design decisions exclusively in the form of a digital model;
- during repairs to lay the track in accordance with the design decisions, and monitor the implementation of these work steps;
- to ensure reliable control of the track position during operation.

The track maintenance is provided by the following sequence of actions: 1) measurement of its full-scale geometrical shape; 2) conformance assessment with maintenance standards; 3) the aim of repair operations. There are various tools for measuring track geometry, from hand-held devices to computerized machine systems [1, 2, 3], including the application of cutting-edge satellite technologies [4, 5]. But any means of measurement requires further conversion of the results into a mathematical model of the railway track.

Despite a large number of scientific and practical developments in dealing with such issues, it cannot be spoken (and it is not necessary) about a single approach in the chain "track survey – formation of a mathematical model of its shape". It is known that both every survey tool and every mathematical method in processing the results have both disadvantages and certain advantages, especially given the task for which they are used [6]. Therefore, for the optimal application of certain track machines, it is needed to have the proper mathematical tool.

The purpose of this paper is to create a mathematical tool to ensure the operation of track machines for surfacing, tamping, and alignment, which are equipped with automation systems. Automation systems are hardware-software complexes for analysis and monitoring the track condition measurements, performing calculations of plan and profile parameters, adjustment of these calculations and control of the surfacing process. Currently, there are many varieties of such machines, but, as a rule, the chord method is applied to survey the shape of the track in them. Moreover, in most cases, the arrow is measured with asymmetrical chord arms, which adds additional complexity for the further mathematical processing of results [7]. One of the variants of such a machine, which is used in Ukraine, is a track renewal train VPR-02 (Fig. 1).

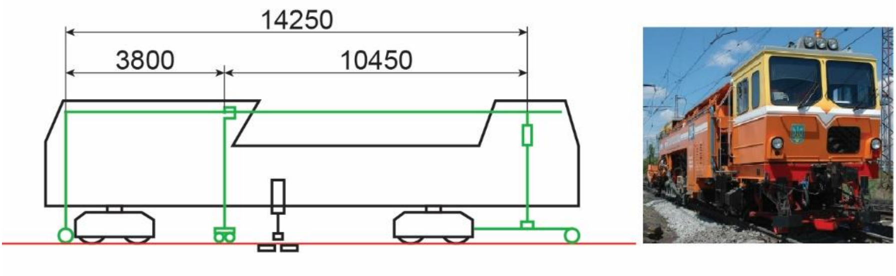

Figure 1. Scheme of VPR-02 machine

The automated system on the basis of the „RWPlan" software complex was installed earlier on machines of this type. It was created by I. P. Korzhenevich for calculations of tracks surfacing [1, 8, 9] (in the horizontal plane). Thus, the system is needed to be supplemented for automated vertical track surfacing.

Correct execution of surfacing allows not only to restore the track geometry in the vertical plane but also to provide the necessary ballast consolidation. The condition of the ballast layer is one of the main factors determining the (structural and geometrical) stability of the track as a whole [10] and the timing of the next repairs [11]. Among other things, high-quality ballast consolidation during surfacing provides uniform track elasticity, which affects the dynamic performances of the track and rolling stock interaction [12]. This is especially true for sections that are structurally elastic, negative of the total length, such as the location of rail joints [13, 14], turnouts [15, 16], etc.

Today, the ballast layer operation is a typical issue of many scientific studies. First of all, these work steps are related to the analysis of the quality and durability of ballast material by contemporary techniques with the involvement of special laboratory devices [17, 18]; with the search in the application of additional substances for ballast, such as the crushed stone of coarse fractions [19], and others.

The latest approaches such as computed tomography (CT scans) [20, 21] and an analysis of wave propagation velocity [22, 23] are applied to study the work of ballast.

2. Methodology

2.1. Measuring the track geometry with an asymmetric chord of the machine

The profile measurement system of a machine consists of two blocks. Longitudinal geometrical deviation are measured by cable systems with potentiometric sensors: lifting right and left rails (Fig. 1). The transverse level of lifting the outer rail is measured by a pendulum system with a potentiometric sensor. The measurement system operates at 625 mm intervals.

In order to select a technique of data processing and construct a mathematical model of the longitudinal profile, the authors analyzed results of surveying the track geometry by machine at several sections. For comparison, geometric leveling of the track was performed with the precision level „Koni-007". Geometric leveling was carried out using "from the inside" technique on two-sided leveling rails of the direct image, the leveling arms were fifty meters, the level installation points were fixed on the side of the track. The leveling was performed on both the outer and inner rails, at 10 m intervals. The leveling line control was carried out according to the established benchmarks (elevation discrepancy of the leveling lines did not exceed 6 mm, at the standard value of 24 mm).

An example of such survey on the Vysun–Utishne section at the Prydniprovska Railway (Ukraine) is shown in Fig. 2.

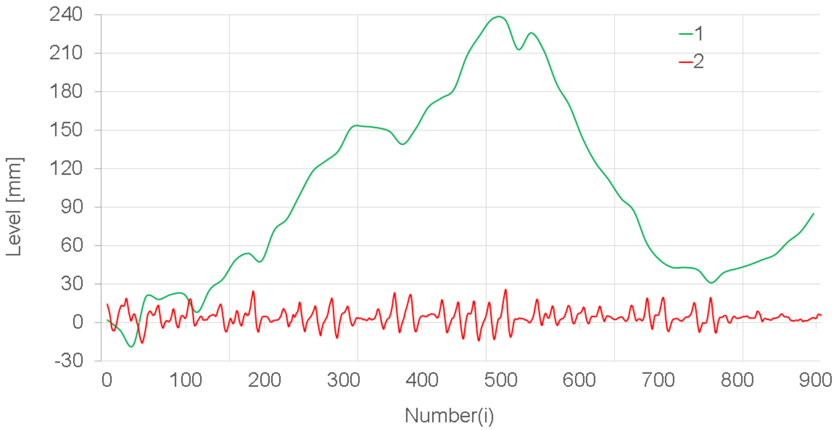

Figure 2. Results of profile survey with Koni-007 level and VPR-02 machine measuring system (1 – results of profile survey with Koni-007 level; 2 – results of profile survey by the machine system)

It is clear that the survey, which is conducted by a chord that equals to the length of the machine, displays the profile in the form of local irregularities, which makes it impossible to directly obtain the profile of a section as a whole (Fig. 2). Thus, it is possible to evaluate only the track condition upon pit-mound indicators along the length of the machine. To create a mathematical model based on such initial data, all possible options for recording inequalities were considered, namely: pit (Fig. 3, a), mound (Fig. 3, b), zero level (Fig. 3, c).

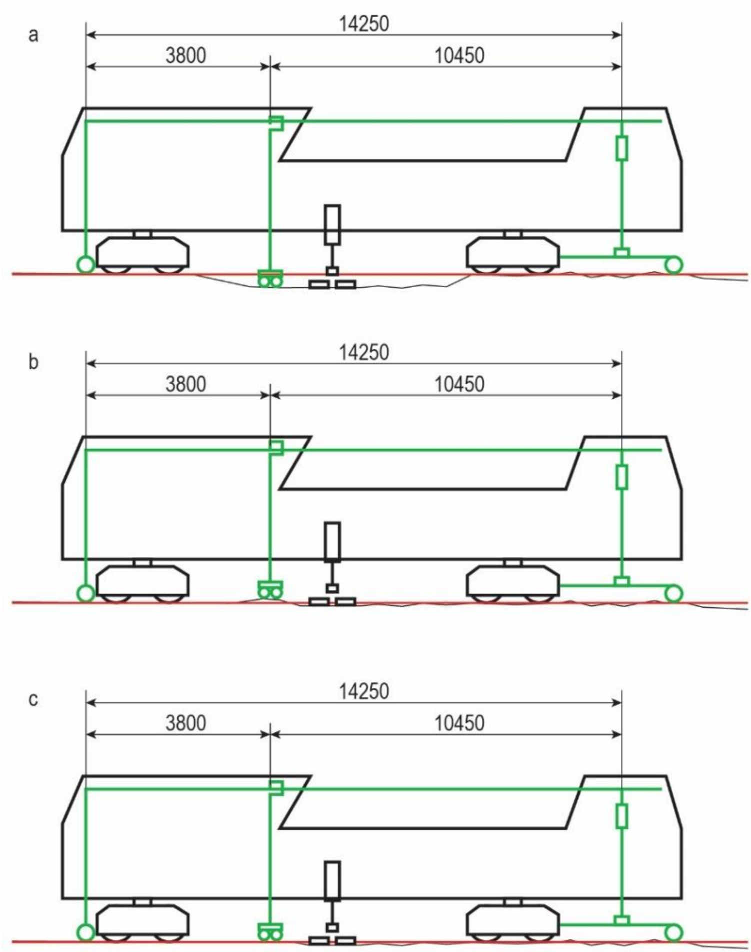

Figure 3. Options for recording irregularities: a) pit; b) mound; c) zero level

2.2. Mathematical model of smoothing track geometry in profile

It is given that the main task of the machine operation is track surfacing in the vertical plane, the main result of mathematical processing of survey data is the value of adjustments to the track position along the length of the section, taking into account the stated restrictions. Restrictions consist of regulatory requirements for track maintenance, technical capabilities of the machine and additional conditions, such as optimizing the use of ballast volumes.

The mathematical model was conditionally divided into five separate functions.

2.2.1. The function of processing negative values of an array

Zero value of the arrow corresponds to the geometrically correct track position, and the local "pit" irregularity (Fig. 3) has negative values and when surfacing, in any case, the track rises at least to "zero value". Therefore, the first function of the mathematical model (conditional name "dataToZero") performs the processing of the source date file/array, and establishes the obligatory lifting for all points that have negative values:

$$\{nu\} = dataZero(\{f | f_i < 0\}), \tag{1}$$

where $\{f\}$ – source array of measured arrows; $\{nu\}$ – the array of adjusted arrows. In the future, this array will be used to calculate the net lifting. The term net lifting will be the difference between the measured and calculated vertical arrow.

Operational algorithm for *dataToZero* function is presented in Fig. 4.

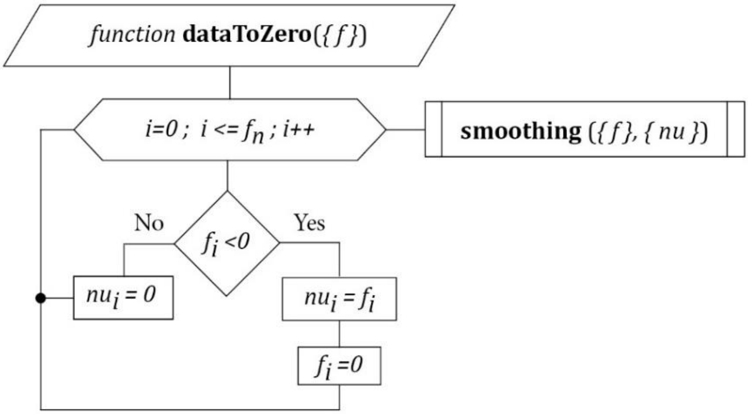

Figure 4. Operational algorithm of dataToZero function

2.2.2. Smoothing calculation function

The function is based on the polynomial of smoothing of experimental data over five points and is a special averaging operation, which – using interpolation polynomials – provides obtaining the design vertical ordinate of the rail $\bar{y}_i$ by adjacent values. Several types of mathematical functions have been previously considered, such as splines, polynomials from the 3rd to 7th degree, and others. For example, an exponential function with a complex basis was used in [24] precisely to reproduce the track profile in line with the results of measurements by a machine with an asymmetric chord, but for the task of establishing a correlation between accelerations and track geometry.

For this work, the authors chose a polynomial of the 5th degree, which at the control number of iterations gave a smoother rail position than the others:

$$\left.\begin{array}{c} \bar{y}_0 = \frac{3\cdot y_0+2\cdot y_1+y_2-y_4}{5}; \\ \bar{y}_1 = \frac{4\cdot y_0+3\cdot y_1+2\cdot y_2+y_3}{10}; \\ \bar{y}_i = \frac{y_{i-2}+y_{i-1}+y_i+y_{i+1}+y_{i+2}}{5} | 2 \le i \le n-2; \\ \bar{y}_{n-1} = \frac{4\cdot y_n+3\cdot y_{n-1}+2\cdot y_{n-2}+y_{n-3}}{10}; \\ \bar{y}_n = \frac{3\cdot y_n+2\cdot y_{n-1}+y_{n-2}+y_{n-4}}{5}. \end{array}\right\} \tag{2}$$

where n – the number of the last point for ordinate y_i.

The selected polynomial (2) was introduced into the algorithm for calculating the track surfacing in profile as $smoothing(\{f\},\{nu\})$ function (Fig. 5).

Fig. 5 presents: $\{p\}$ – source array of net liftings; $\{nf\}$ – source array of smoothed arrows; $countCycles$ – number of calculations cycles; $countCyclesLimit$ – maximum number of cycles; $upLimit$ – conditional switch, obtained from $checkingUp(\{p\})$ function (more information in Section 2.2.3); checkingUpLimit($\{nf\},\{p\}$**)** is a checking function of lifting sufficiency to ensure the calculated elevation (more information in Section 2.2.4).

2.2.3. Checking function of ensuring restrictions in machine design

Since the design of the machine has restrictions on the maximum lifting (for machines VPR-02 this value is 100 mm), and restrictions on the thickness of the ballast can be imposed, the checking function of restrictions (*checkingUp* ({p})) was added into the mathematical model (Fig. 6).

Fig. 6 presents: F_{max} – the maximum permissible lifting (defined by the operator); F_{min} – the minimum lifting, a static value associated with the machine design; $maxUp$ – restriction on the maximum lifting conforming to the machine design (for VPR-02 this value is 100 mm); hrw – the array of calculated (design) elevations of outer rail relative to the inner rail.

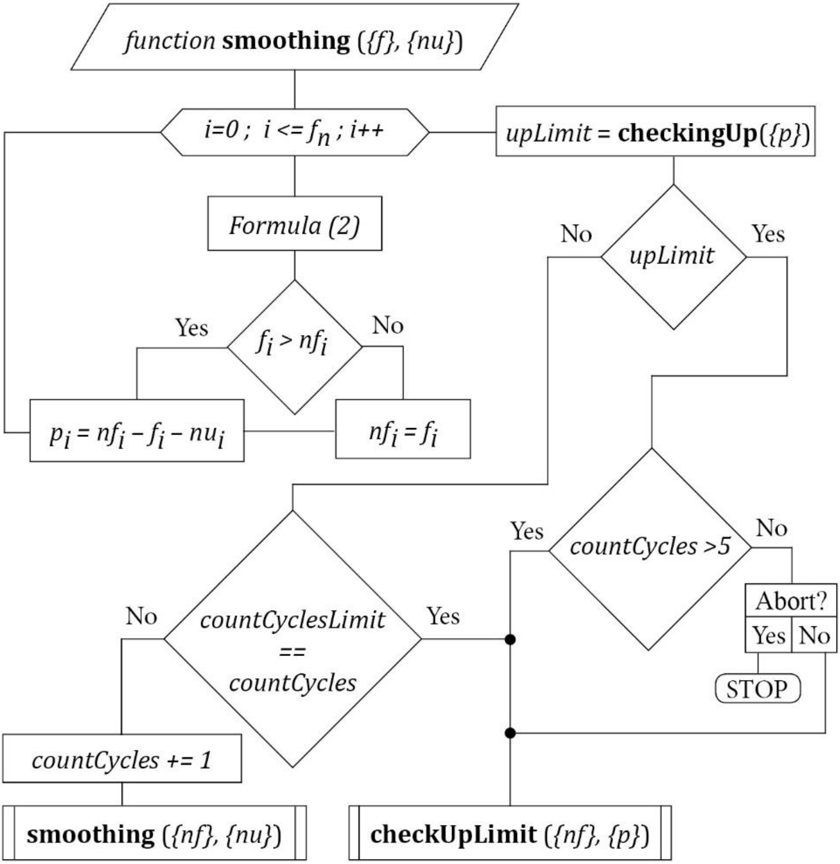

Figure 5. Operational algorithm of smoothing function

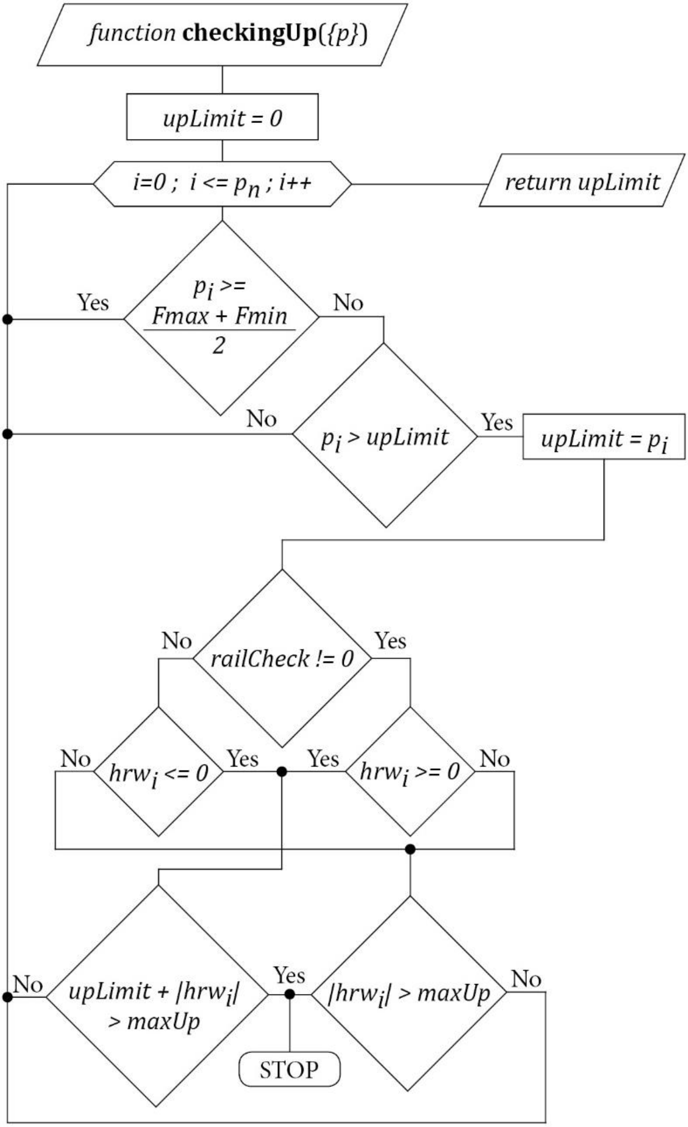

Figure 6. Operational algorithm of checkingUp function

2.2.4. Checking function of lifting sufficiency for ensuring the calculated elevation

The pendulum system of the machine is used to insert the second calculating rail in the design position. The machine raises one rail to the design height in accordance with the vertical arrows obtained as a result of calculations, and the position of the second rail is set according to the calculation for the elevation from the program (exactly for VPR-02 machine this is done in the "RWPlan" software package [8]). However, while surfacing the track, there may be boundary conditions under which the calculated lifting may not be sufficient to provide the design elevation, due to the above design constraints of the machine or for other reasons. Five cases were considered to introduce a test for the possibility of providing a design elevation in the mathematical model.

- *The first boundary condition.* Net lifting p_i at the calculated point is greater than zero, calculated elevation hrw_i is less than measured ma_i (Fig. 7).

Figure 7. The first boundary condition
(in this and subsequent Figures, the existing position for assembled rails and sleepers are shown in gray solid color, the calculated position is in green)

- *The second boundary condition*. Net lifting p_i at the calculated point is equal to zero, calculated elevation hrw_i is less than measured ma_i (Fig. 8).

Figure 8. The second boundary condition

- *The third boundary condition*. Net lifting p_i at the calculated point is more than zero, calculated elevation hrw_i is equal to zero, measured elevation ma_i is greater than zero (Fig. 9).

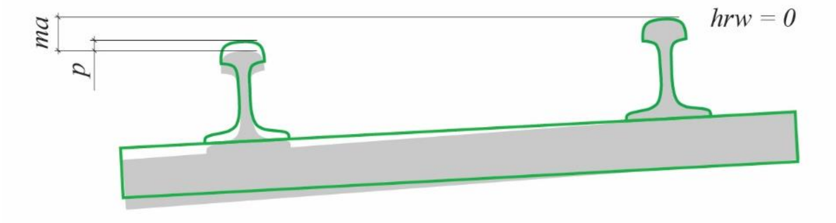

Figure 9. The third boundary condition

- *The fourth boundary condition.* Net lifting p_i at the calculated point is more than zero, calculated elevation hrw_i is greater than measured elevation ma_i (Fig. 10).

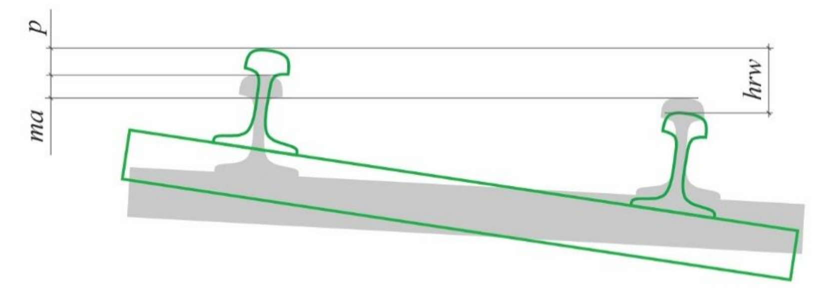

Figure 10. The fourth boundary condition

- *The fifth boundary condition.* Net lifting p_i at the calculated point is more than zero, calculated elevation hrw_i greater than zero, measured elevation ma_i is equal to zero (Fig. 11).

Figure 11. The fifth boundary condition

Fig. 7-11 are given for the left calculatied rail, the same conditions has to be applied to the right rail.

To take into account all the above boundary conditions the checking function of the lifting sufficiency was included in the mathematical model to provide the calculated elevation *checkingUpLimit*($\{nf\}, \{p\}$) (Fig. 12).

If the above conditions are violated, the function makes adjustments to the calculation and returns the data array for re-smoothing, after which the test cycle is repeated until the boundary conditions.

2.2.5. Function of compensation for the uncounted additional lifting of the machine

When surfacing the profile by the machine, a situation arises when the rear control device of the leveling machine system is already on the corrected section of the track, and the front control device on yet not corrected one, hence, arrows measured during the survey are no longer true and the calculation requires adjustment by the value of h, see Fig. 13. Moreover, this adjustment should be made only where it is needed, i.e. only in the presence of the above situation.

The adjustment amount h is calculated based on the given machine geometry (Fig. 14).

Based on Fig. 16, adjustment amount h, is shown in the figure as the segment Q_1M, calculated by the formula:

$$Q_1M = \frac{NA_1 \cdot Q_1D_1}{A_1D_1}. \quad (3)$$

This formula is added to the mathematical model for calculating the track surfacing in the profile in the form of $extraLiftUp$ ($\{nf\}$) function, where $\{nf\}$ is the source array of smoothed and tested under boundary conditions arrows (Fig. 15).

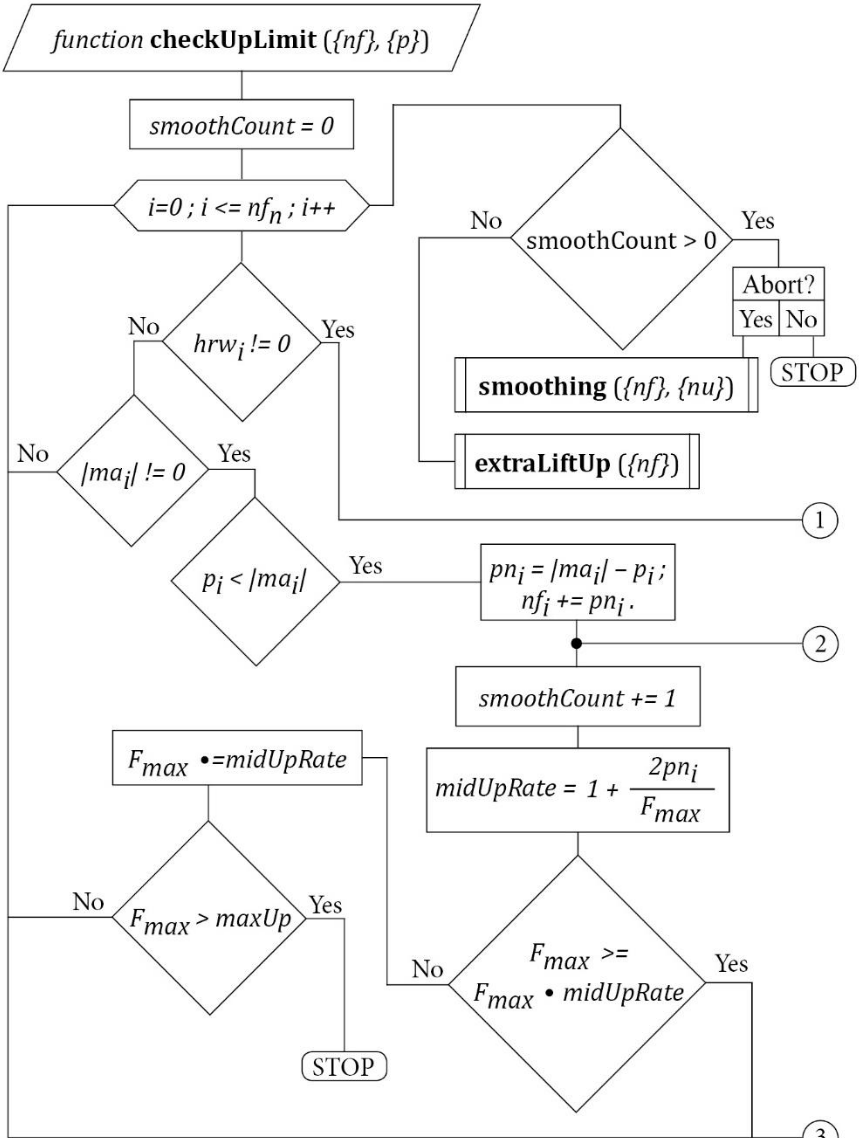

Figure 12. Operational algorithm of checkingUpLimit function (Part 1)

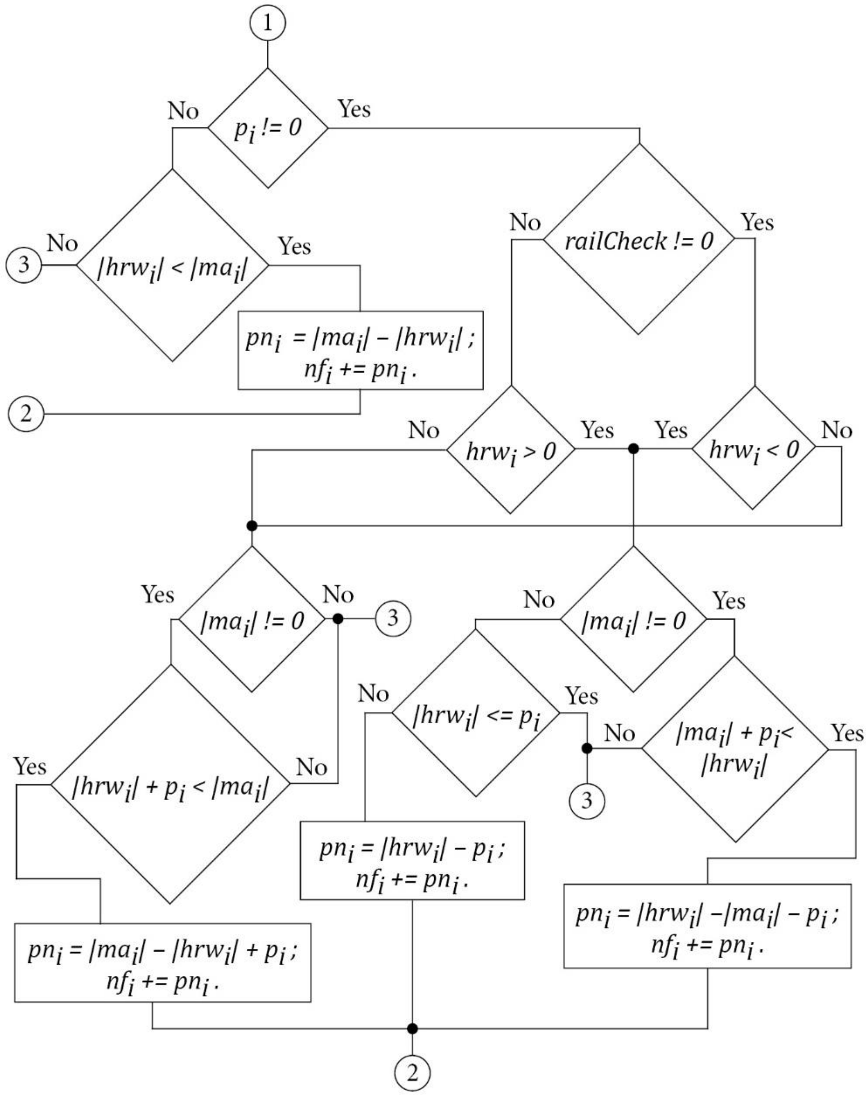

Figure 13. Operational algorithm of checking UpLimit function (Part 2)

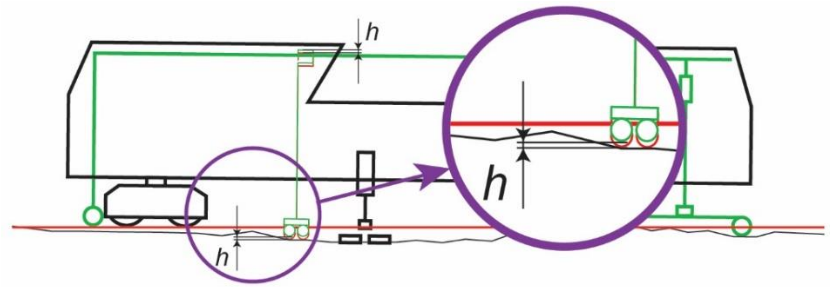

Figure 14. The adjustment amount of calculated lifting

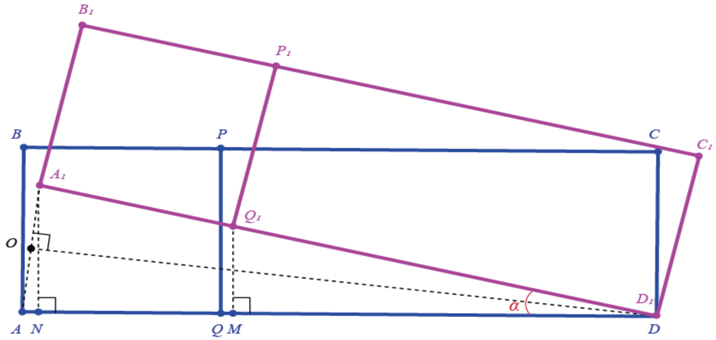

Figure 15. Computation scheme of correction h

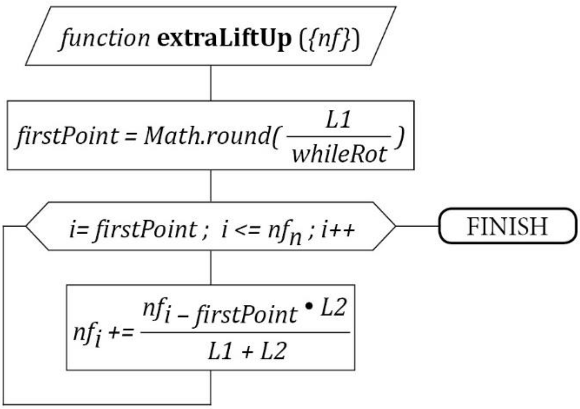

Figure 16.The function of compensation for the unaccounted additional lifting of the machine

Fig. 16 presents: $firstPoint$ – the first point for calculating the additional lifting; $L1$ – distance from the rear control device to the survey unit of the machine; $L2$ – distance from the survey unit to the front control device.

The function calculates the point from which one needs to make corrections and adds the calculated adjustment amount h to the arrow thereby increasing the original calculated arrow.

3. Results

On the basis of the developed mathematical model, the AS "Strela" software package was developed. To test the operability of the software package, field tests were conducted in the following sequence:

- the machine conducts a measuring run and records the track geometry;
- the machine operator uses the AS "Strela" software package that calculates the required liftings;
- the machine performs the run for the track surfacing into the design position;
- the machine performs a measuring run to record the track geometry after surfacing.

The results of one of these tests are shown in Fig. 16–20.

After the measuring run of the machine, the results were obtained on the left rail, shown in Fig. 16. As it can be seen the track profile has many irregularities and needs to be corrected.

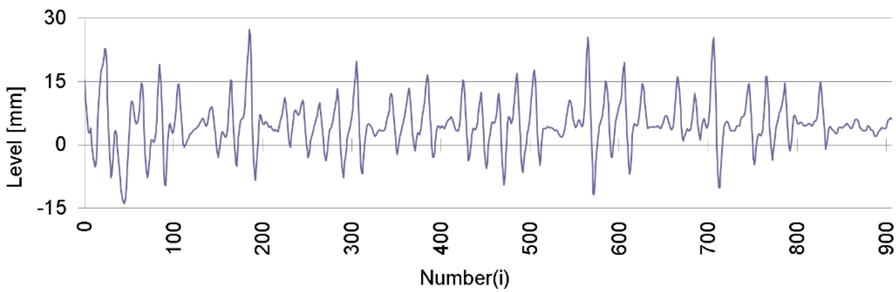

Figure 17. Measurement result with the VPR machine for the left rail

After calculating the track surfacing, the calculated track position shown in Fig. 17 was obtained.

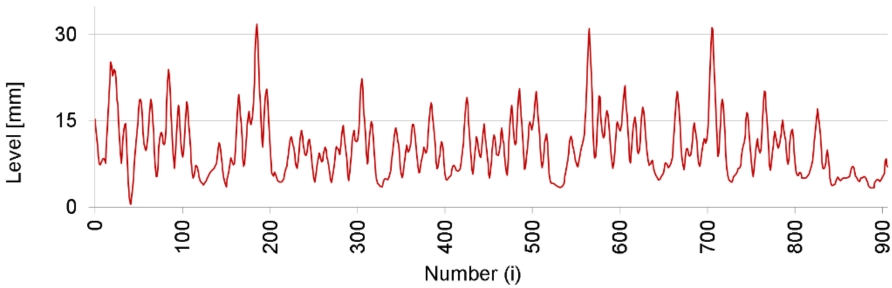

Figure 18. Calculation data with the mathematical model for the left rail

For comparison, the authors present a combined graph of measurement results and the calculated position (Fig. 18).

After the surfacing, a measuring run was made again (Fig. 19).

The combined graph of the calculation model and control measurements by the VPR machine is shown in Fig. 20 and 21.

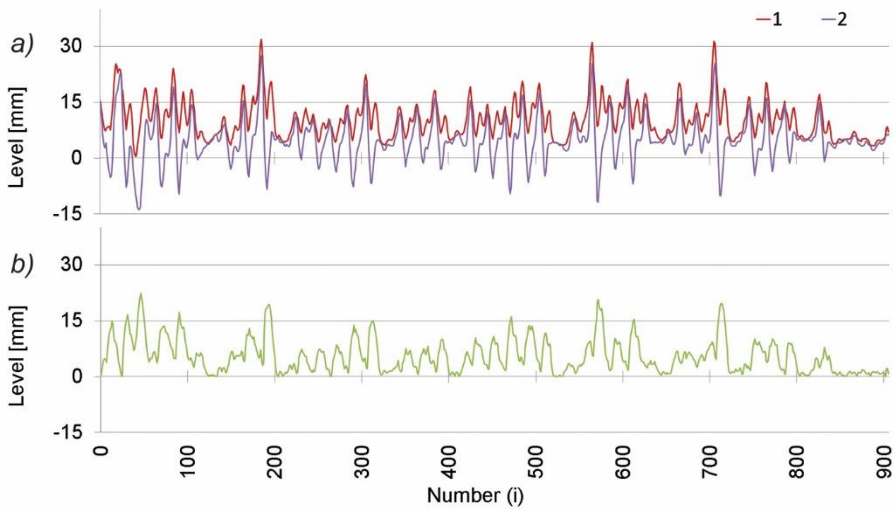

Figure 19. Combined graph of measurement (a1), calculation results (a2) and difference (b) on the left rail

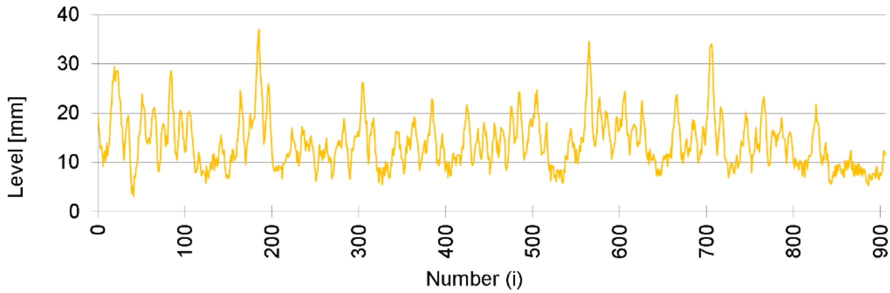

Figure 20.The results of control measurements by the VPR machine after surfacing for the left rail

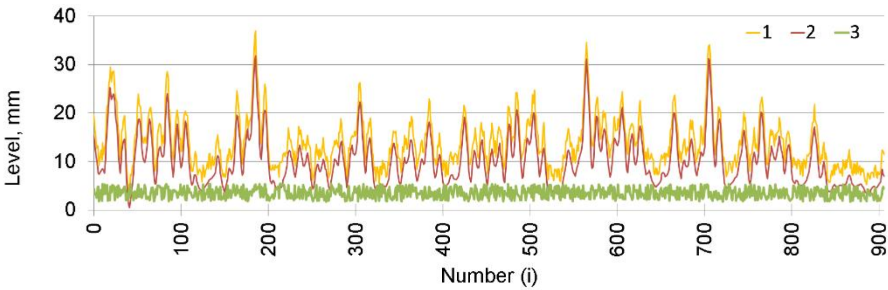

Figure 21.Combined graph of the control measurements (1), calculation model (2) and difference (3) by the VPR machine

4. Conclusions

The developed mathematical model will be integrated into the AS "Strela" software package which is currently installed on seven VPR-02 machines after their overhaul at the Ukrainian plant LLC "RPC Dniprospetsmash". The machines passed field tests and were put into operation.

Scientific approaches used in the mathematical model allowed to reduce the operation of machines in "window", to simplify the work of maintenance personnel, to create an information base of track parameters, to establish rational parameters of curves while surfacing.

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