optimization, numerical procedure, Gradient Projection Method,
Finite Element Method, bearing structure, body, track machine,
deflected mode, durability, testing

Bogdan TOVT
Dnipropetrovsk National University of Railway Transport named after Ac. V. Lazaryan
Academician Lazaryan st., 249010, Dnipropetrovsk, Ukraine
Corresponding author. E-mail: tovt@ua.fm

IMPROVEMENT OF DESIGN TECHNIQUE OF TRACK MACHINES BODIES BEARING STRUCTURES

Summary. The paper is devoted to improvement of design technique of track machines bodies bearing structures. The review and analysis of state-of-the-art of the mathematical programming theory and the optimal designing are done. The numerical optimization procedure for track machines bodies bearing structures is proposed. The approbation of the proposed procedure is taken on structural optimization problems. Mathematical aspects of proposed procedure implementation are investigated, particularly the algorithm convergence and the sensitivity analysis of initial designs.

Deflected mode of the ballast leveling machine SPZ-5/UA body bearing structure was investigated analytically (FEM study) and experimentally (trial running inspection on durability). The necessity of optimization implementation for bodies bearing structures is substantiated. The rational design of track machine SPZ-5/UA bearing structure was obtained with the numerical optimization procedure proposed in the paper. The deflected mode of the body rational bearing structure was investigated.

УСОВЕРШЕНСТВОВАНИЕ ТЕХНОЛОГИИ ПРОЕКТИРОВАНИЯ НЕСУЩИХ КОНСТРУКЦИЙ КУЗОВОВ ПУТЕВЫХ МАШИН

Аннотация. Статья посвящена усовершенствованию технологии проектирования несущих конструкций кузовов путевых машин. Выполнен обзор и анализ современного состояния теории математического программирования и оптимального проектирования. Предложена численная процедура оптимизации несущих конструкций кузовов путевых машин. Проведена апробация предложенной процедуры на ряде задач оптимизации конструкций. Исследован ряд математических аспектов использования предложенной процедуры, в частности сходимость алгоритма процедуры и анализ чувствительности начальных проектов.

Исследовано напряжённо-деформированное состояние (НДС) несущей конструкции кузова планировщика балластной призмы СПЗ-5/UA аналитическим и экспериментальным путём. Обоснована необходимость проведения оптимизации несущей конструкции кузова рассмотренной машины. При помощи предложенной в работе численной процедуры оптимизации получен рациональный проект несущей конструкции путевой машины СПЗ-5/UA. Исследовано НДС рациональной несущей конструкции кузова рассмотренной путевой машины.

1. INTRODUCTION

A railway transport plays a key role in development of Ukraine national economy and conception of development of railway transport and speed motion of passenger-trains is for today worked out and calculated. In accordance with conception of organization of speed motion on the tracks of Ukraine the stage-by-stage rev-up of motion is foreseen on existent lines to 200 km/h with next building of the special speed highways. High-quality and effective realization of the marked program depends on the state of rolling stock on the whole, and track machines stock which produce works from permanent repair and maintenance of railway tracks, in particular.

Therefore the theme of paper, sanctified to the improvement of technique of design of bearing structures of bodies of track machines, it follows to consider actual scientific and technical problem.

The government scientific and technical program of creation of speed highways foresees the substantial restructure of overhead structure of railway that in turn results a necessity for perfection of existing and creation of new structures of track machines with the improved techno-economic indexes, by the strength property increased in particular and lower materials consumption.

Solution of problems of the increase of strength property and decline of materials consumption of both existent bearing structures of track machines and those which are designed, requires the improvement of technique of design of bearing structures of bodies of track machines. One of possible ways of such improvement consists in bringing in modern methods of designing, among which it is possible to distinguish the optimal designing.

2. THE NUMERICAL OPTIMIZATION PROCEDURE FOR BEARING STRUCTURES OF TRACK MACHINES BODIES

A structural optimization theory is that key trend of science on the base of achievements of which mechanical structures must be created. The structural optimization theory began actively to develop in 60th, last decades formed new directions, considerable results, both theoretical and applied, were made. Amount of the publications sanctified to the structural optimization theory grows. A considerable contribution to development of theory and development of methods of solution of structural optimization problems were brought in by such scientists, as Aropa, Haug, Haftka, Gill, Keller, Levi, Mruz, Niordson, Olhoff, Prager, Reklaitis, Rosen, Rozvany, Taylor, Terner, et al. Among home scientists have most homage such as Banichuk, Poschtman, Vinogradov, Goldstein, Smirnov et al.

The preponderant number of numerical optimization methods requires the calculation of state variables at the action of the certain loading and also gradients of functions which set constraints on the design and state variables. At consideration of composite engineering structures which the bearing structures of track machines bodies belong to determination of state variables most effective is Finite Element Method (FEM), but its use in optimization procedure causes some difficulties. Videlicet, absence of analytical dependence of coefficients of stiffness matrix of structure from the design variables is not possible in the explicit form gradients of functions, which set a constraint on state variables.

Iteration procedure is offered for the solution of optimization problems of track machines bodies bearing structures. This procedure is based on use of standard bundled software what will realize FEM and one of widespread methods of the constrained optimization – Gradient Projection Method.

2.1. Procedure statement

We use in the next follow table of symbols: initial design b^0, allowable design b^j, intermediate design w^j, admissible error in active constraints definition ε_1, admissible convergence error ε_2, active constraint set D, objective function ψ_0, constraint functions $\psi_i, i = 1,...,n,...,m$, objective function gradient in b^j – $\nabla\psi\left(b^j\right)$, projective matrix P, matrix of the gradients of state variables constraint functions A, vector, which set iteration scheme course s, normalize multiplier λ, step parameter α, state variables residual h, Lagrangian coefficients $\left(v,u\right)$, unity matrix I.

The problem of nonlinear mathematical programming in formal statement will formulate thus:

Let's find such vector of design variables (the design project) $b \in R^k$, which minimizes objective function $\psi_0(b)$ at the set constraint $\psi_i(b)=0, i=1,...,n,\ \psi_i(b)\le 0, i=n+1,...,m.$

For the problem solution we use the Gradient Projection Method [1, 2] which algorithm is based on that each iteration objective function decreases, and constraints aren't violate.

The basic complexity to use the Gradient Projection Method for real structures optimization is represented by the procedure of calculation of the matrix of gradients of the functions setting constraints on design variables and state variables of structure.

The matrix of gradients A looks like [3]:

$$A=\left(\frac{\partial\psi(B,Z)}{\partial B}\right)^T=\begin{bmatrix} \frac{\partial\psi_1}{\partial b_1} & \frac{\partial\psi_1}{\partial b_2} & \cdots & \frac{\partial\psi_1}{\partial b_j} \\ \frac{\partial\psi_2}{\partial b_1} & \frac{\partial\psi_2}{\partial b_2} & \cdots & \frac{\partial\psi_2}{\partial b_j} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial\psi_m}{\partial b_1} & \frac{\partial\psi_m}{\partial b_2} & \cdots & \frac{\partial\psi_m}{\partial b_j} \end{bmatrix}, \tag{1}$$

where: Z – state variables vector of dimension m; B – design variables vector of dimension j.

Matrix elements $\frac{\partial\psi(B,Z)}{\partial B}$ can be defined derivation of analytical dependences of constraints from design variables. But in optimization of real mechanical structures it is almost impossible to receive such dependences, therefore it is offered to receive making elements of the constraint matrix numerically. With that end in view we use known expression for calculation of partial derivatives of many variable functions [11]:

$$\frac{\partial\psi_i}{\partial b_k}=\frac{\psi_i(b_1,b_2,...,b_k+\Delta b_k,...,b_j)}{\Delta b_k}-\frac{\psi_i(b_1,b_2,...,b_k,...,b_j)}{\Delta b_k}. \tag{2}$$

Definition of function values ψ_i is carried out by design calculation of Finite Elements Method (FEM). Namely, at first the stress σ_i' in an element for which constraint is set is defined, then, after a k-parameter increment, calculation is repeated and the stress σ_i'' is defined at the changed value of k-parameter.

The elements of constraint matrix are defined so:

$$\frac{\partial\psi_i}{\partial b_k}=\frac{\sigma_i''-\sigma_i'}{\Delta b_k}. \tag{3}$$

For the purpose of quality standard of influence of variations of design variables on the objective function expression is used:

$$\frac{\partial\psi_i}{\partial b_k}=\frac{\sigma_i''-\sigma_i'}{\Delta b_k}\cdot\lambda\quad, \tag{4}$$

where: λ – normalize multiplier which is calculated according to expression:

$$\lambda=\frac{1}{\sqrt{\sum_{j=1}^{m}\left(\frac{\sigma_i''-\sigma_i'}{\Delta b_k}\right)^2}}. \tag{5}$$

It is possible to name the necessity count of the structure the lack of such procedure by the FEM [4]. However it is leveled by the modern level of development of the computing engineering. The important feature of the offered procedure is a small dimension of matrix of constraints. For example to the problems of mechanics of the deformed body, structure durability at some type of loading is conditioned by few elements durability. It goes out from it, that a number of constraints functions by durability and dimension of matrix of constraints A will be small.

Under the offered procedure, state variables are determined directly with the use of FEM at every step, and gradients of functions, which set constraints on them, – indirectly, with the use of numerical approximation. Thus the use of such procedure allows avoiding foregoing difficulties during optimization of the real track machines structures.

2.2. Procedure algorithm

The algorithm of the numerical optimization procedure for bearing structures of track machines bodies is formulated as follows:

Step 0. For active set definition

$$D = \left\{ i : \varphi_i \left(b^j \right) \le \varepsilon_1, i = 1, ..., J \right\}$$

calculate in b^j constraints in inequality view.

Step 1. Calculate P, $s = -P \nabla \psi_0 \left(b^j \right)$ and λ, matrix A is making by (1), and matrix elements are defined by (2), (3) and (4), λ calculated by (5). The weighting matrix W may be set with necessity.

$$P = W\left(I - \lambda A^T \left(AA^T \right)^{-1} A \right).$$

Step 2. If $\left\| s \right\| > \varepsilon_2$, go to step 3. Otherwise calculate Lagrangian coefficients

$$\left(v, u \right) = \left(AA^T \right)^{-1} A \nabla \psi_0$$

and search

$$u_{\mathrm{m}} = \min \left\{ u_l : l \in D \right\}.$$

If $\left| u_m \right| \le \varepsilon_1$, stop calculating. Otherwise except constraint m from active set D and go to step 1.

Step 3. Define such maximal step length $\alpha_{\max}$, and $\varphi_l \left(w(\alpha) \right) \ge 0$ for all $l \notin D$. For each α function $w(\alpha)$ is iteration result:

$$w^t = b^{j-1} + \alpha s$$

$$w^{t+1} = w^t - \lambda A^T \left(AA^T \right)^{-1} h.$$

$$b^j = w^{t+1}$$

with compliance all constraints and return to Step 1.

If at least one of defined constraints is non-compliance repeat calculation by (6) until all constraints are not satisfied.

2.3. Procedure approving

The numerical procedure was approved on the number of problems of optimization of structures, similar to the most widespread bearing structures track machines. For test optimization was select a truss, which does not contain a central longitudinal element (7-bar truss, Fig. 1, farther structure *A*) and a truss which contains a central longitudinal element (6-bar truss, Fig. 2, farther structure *B*). At both structures constituent elements had a rectangular cross-section. Structure *A* is under concentrated load (Fig. 1). Structure *B* is under distributed load (Fig. 2).

As design variables for both structures the parameters of cross-sections of constituent elements were selected, thus they were accepted by permanent under length of corresponding element.

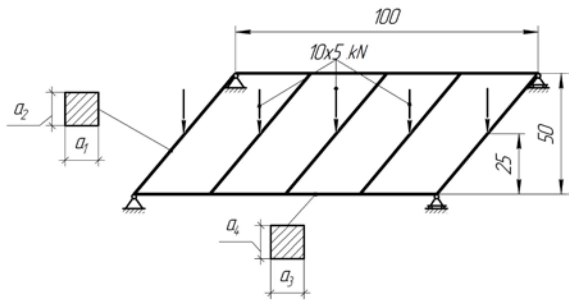


Fig. 1. 7-bar truss structure
Рис. 1. Конструкция 7-балочного ростверка

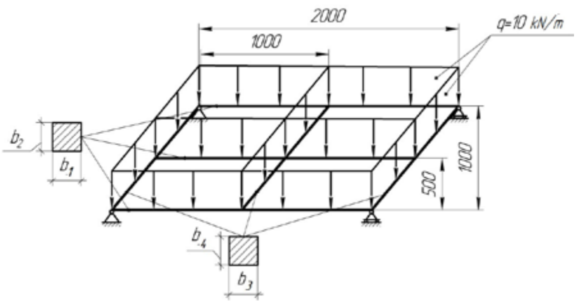


Fig. 2. 6-bar truss structure
Рис. 2. Конструкция 6-балочного ростверка

Vector of design variables for a structure *A* looks like $\vec{a}^0 = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \end{bmatrix}^T$, where a_1, a_2, a_3, a_4 – are parameters of cross-sections of constituent elements of structure *A* (Fig. 1).

Vector of design variables for a structure *B* looks like $\vec{b}^0 = \begin{bmatrix} b_1 & b_2 & b_3 & b_4 \end{bmatrix}^T$, where b_2 and b_4 – are heights of cross-sections of constituent elements of structure *B*, b_1 and b_3 – widths of cross-sections of beams of the truss *B*, permanent sizes within the framework of this problem $b_1 = b_3 = 4$ cm (Fig. 2).

As objective function for both structures a general volume was selected because the main circuit of these problems was decrease of structure mass. Objective function for a structure *A* has expression:

$$\psi_{0A} = 5 \cdot (50 \cdot a_1 \cdot a_2) + 2 \cdot (100 \cdot a_3 \cdot a_4),\ \text{cm}^3.$$

Objective function for a structure *B* has expression:

$$\psi_{0B} = 100 \cdot 3 \cdot \left(b_1 \cdot b_2\right) + 200 \cdot 3 \cdot \left(b_3 \cdot b_4\right),\ \text{cm}^3.$$

Constraints on state variables for both structures were set identically – as strength condition by possible stresses:

$$\sigma^{(i)} - [\sigma] = 0,$$

where: $\sigma^{(i)}, i = 1,2$ – real stresses in the corresponding elements of structure;

$\left[\sigma\right]$ – allowable stress, accepted $\left[\sigma\right] = 200$ MPa.

The design variable constraints were also set identically – as a condition of inalienability of structure sizes:

$$a_k > 0,\ k = 1,...,4,\ \ b_k > 0,\ k = 2,4.$$

or a structure *A* two initial designs $\vec{a}_1^0 = \begin{bmatrix} 3 & 4 & 3 & 5{,}5 \end{bmatrix}^T$ and $\vec{a}_2^0 = \begin{bmatrix} 3{,}5 & 3{,}5 & 4{,}5 & 4{,}5 \end{bmatrix}^T$ were selected, for a structure *B* – four initial designs $\vec{b}_1^0 = \begin{bmatrix} 4 & 6 & 4 & 8 \end{bmatrix}^T$, $\vec{b}_2^0 = \begin{bmatrix} 4 & 7{,}3 & 4 & 7{,}3 \end{bmatrix}^T$, $\vec{b}_3^0 = \begin{bmatrix} 4 & 10 & 4 & 8 \end{bmatrix}^T$ and $\vec{b}_4^0 = \begin{bmatrix} 4 & 4 & 4 & 4 \end{bmatrix}^T$ thus the last was in an prohibitive zone in obedience to constraints on state variables.

Progress of optimization procedure for a structure *A* presented by the graph of change of objective function depending on an iteration (Fig. 3). Will mark that character of design variables change for this problem coincides with character of objective function change.

Analysis of results of weight optimization 7-bar truss showed that the choice of different initial designs did not influence on final result – receipt of only optimal design (Fig. 3). An optimal design was attained after 28 and 37 iterations depending on an initial design. As a result of weight optimization 7-bar truss it was succeeded to get a 56 % diminishing of structure weight (Tab. 1).

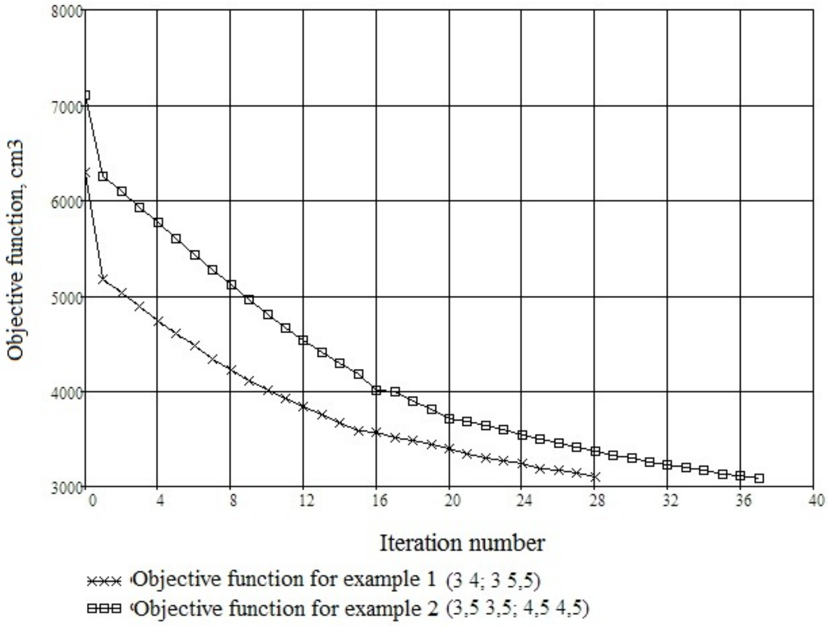


Fig. 3. Objective function of the problem of 7-bar truss optimization
Рис. 3. Целевая функция задачи оптимизации 7-балочного ростверка

Table 1

The results of 7-bar truss weight optimization

Initial design	Diminishing objective function, %	Iteration number
$\vec{a}_1^0$	51	28
$\vec{a}_2^0$	56	37

Progress of optimization procedure for a structure *B* illustrated by the graphs of change objective function depending on iteration (Fig. 4), and also designs variables depending on an iteration (Fig. 5, 6). On the objective function changes graph is not shown optimization progress from an initial design which were in a prohibitive zone.

Analysis of results of weight optimization 6-bar truss confirmed again that the choice of different initial designs does not influence on the receipt of optimal solution of problem (Fig. 4 - 6). Thus at the choice of initial design $\vec{b}_4^0$ in a prohibitive zone (Fig. 5, 6) as a result of optimization the same eventual design was done as well as at the choice of initial designs in a possible zone which testifies to algorithm procedure convergence. An optimal design was attained after 4, 7, 12 and 5 iterations, depending on an initial design. As a result of optimization 6-bar truss it succeeded to get 114% diminishing of structure weight (Tab. 2).

Table 2

The results of 6-bar truss weight optimization

Initial design	Diminishing objective function, %	Iteration number
$\vec{b}_1^0$	11,4	4
$\vec{b}_2^0$	10,8	7
$\vec{b}_3^0$	10,8	12
$\vec{b}_4^0$	–	5

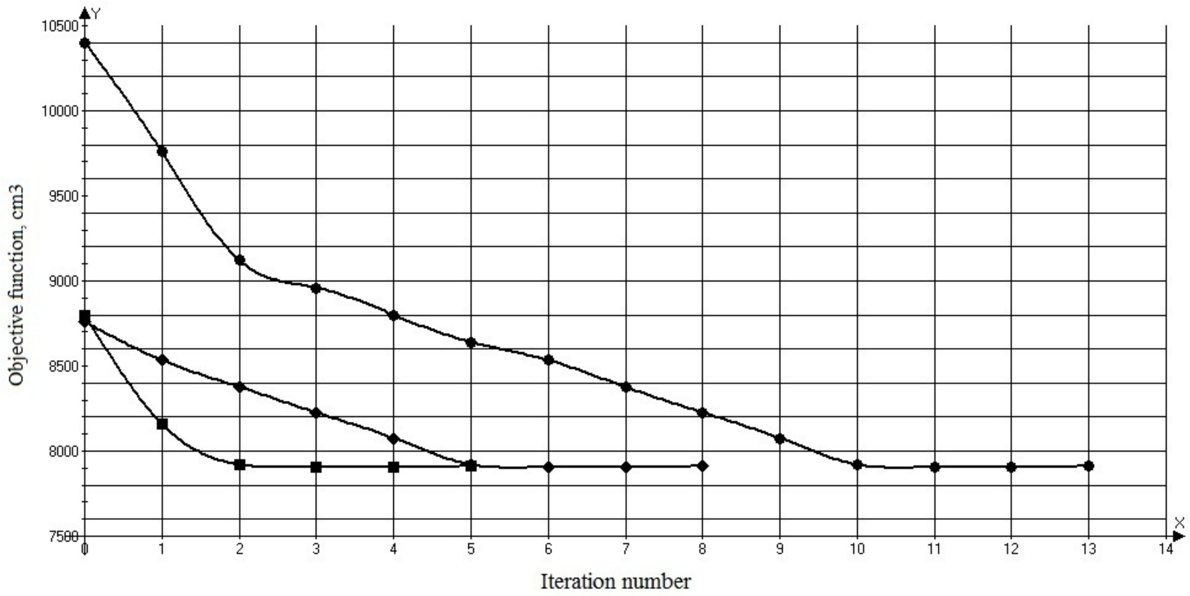


Fig. 4. Objective function of the problem of 6-bar truss optimization
Рис. 4. Целевая функция задачи оптимизации 6-балочного ростверка

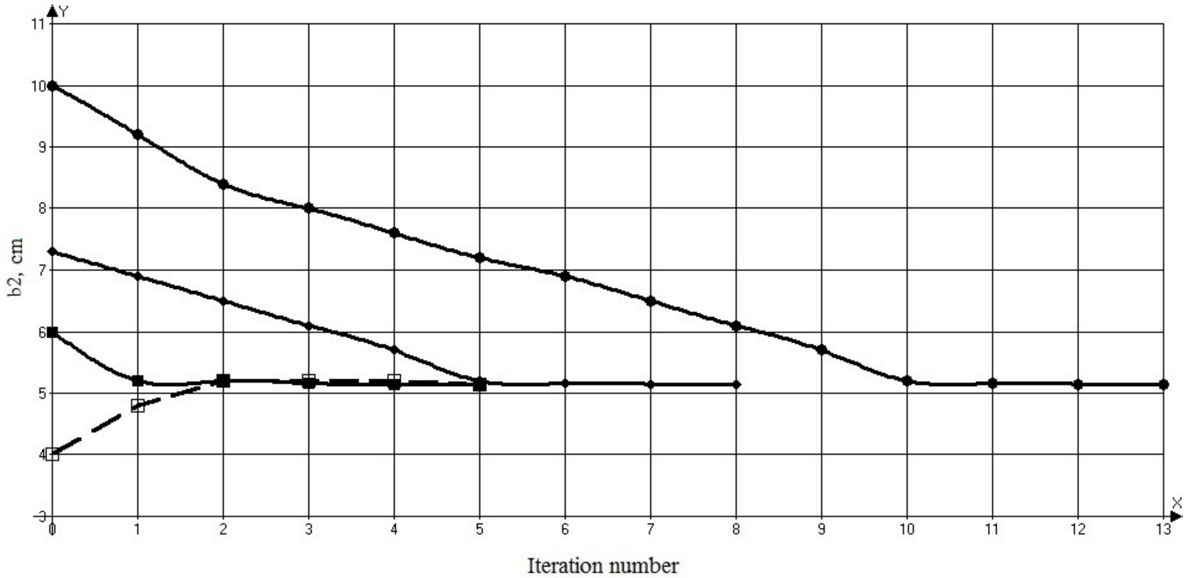


Fig. 5. Design variable b_2 of the problem of 6-bar truss optimization
Рис. 5. Переменная проектирования b_2 задачи оптимизации 6-балочного ростверка

3. THE RESEARCH OF THE DEFLECTED MODE AND OPTIMIZATION OF THE BEARING STRUCTURE OF BALLAST LEVELING MACHINE SPZ-5/UA

3.1. The research of the deflected mode of ballast levelling machine SPZ-5/UA

A ballast leveling machine is used in the track facilities and is designed for making the final shaping of the track ballast [5].

The ballast leveling machine SPZ-5 has three operating mode: worker, self-propelled and transport. The research of the deflected mode of the bearing structure of ballast leveling machine SPZ-5/UA was conducted by five types of loading: loading from forces of own weight of the bearing structure and equipment set on it in a transport mode (there is the mode of the static loading recognition to the dynamic factor) and also from four varieties of loading in operating modes (“A”, “B”, “C”, “D”), depending on technological operations which are executed.

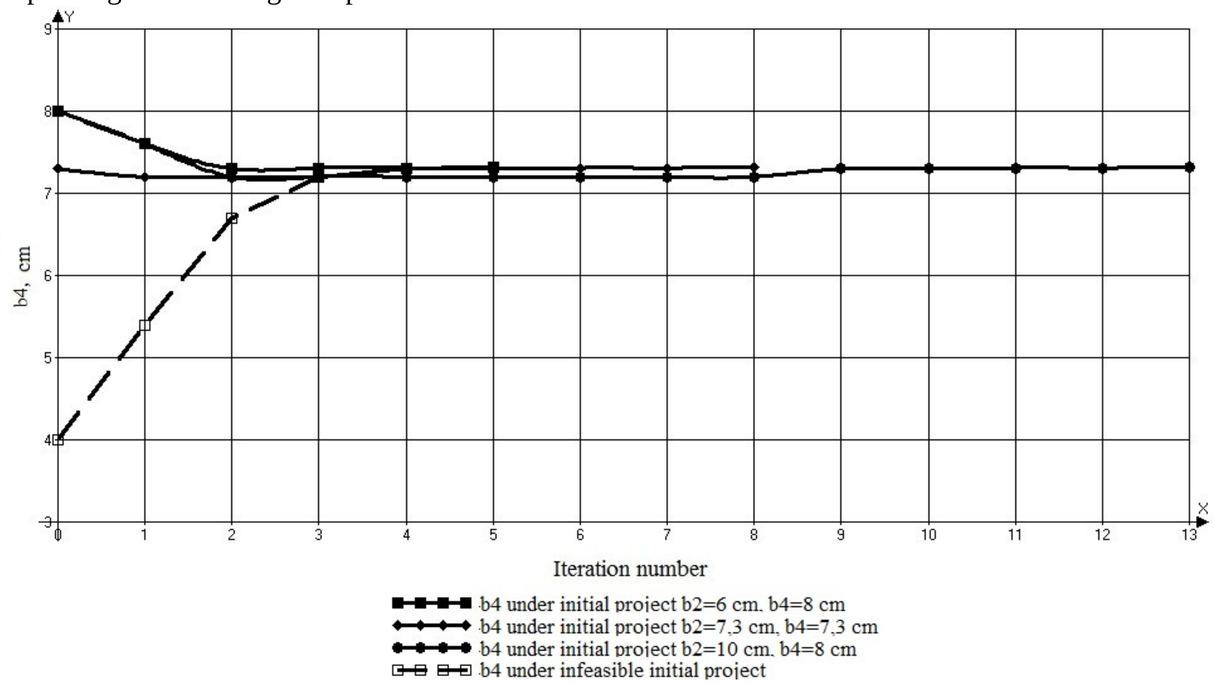


Fig. 6. Design variable b_4 of the problem of 6-bar truss optimization

Рис. 6. Переменная проектирования b_4 задачи оптимизации 6-балочного ростверка

By the aim of research of deflected mode of bearing structure of ballast leveling machine SPZ-5/UA by the FEM [10] is verification of accordance of construction to the terms of durability and determining the locations of establishment of strain transducer is for realization of working durability tests of machine. Except that on results the calculation of bearing structure of ballast leveling machine by FEM static stresses σ_{st} were defined with a following estimation to the safety factor of fatigue resistance n. The general view of FE-model of truss of planner together with loading from forces of own weight and working equipment set on a truss is shown on Fig. 7.

The research of deflected mode of bearing structure of ballast leveling machine SPZ-5 in a transport mode showed that middle part of structure was the most loaded. In the stress concentration zone a maximal value of equivalent stresses is in the theory of durability of von Misses recognition to the dynamic factor, which was accepted $k = 1{,}5$ [7], makes about 82,5 MPa (Fig. 8, a) which is considerably below than allowable stress, that is 155 MPa for the steel 09Г2 [6, 7].

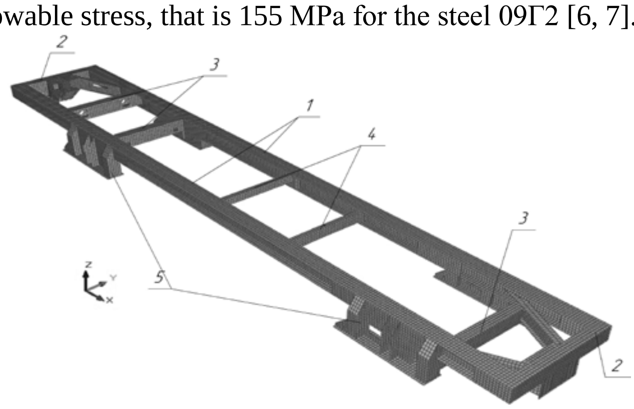
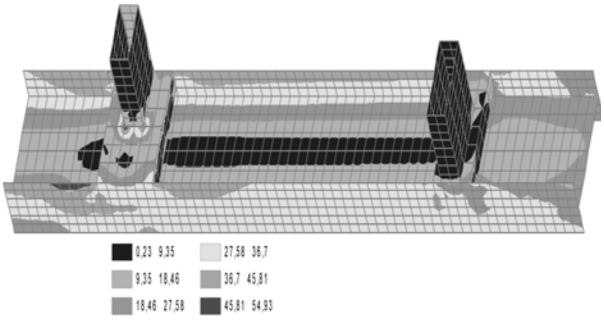
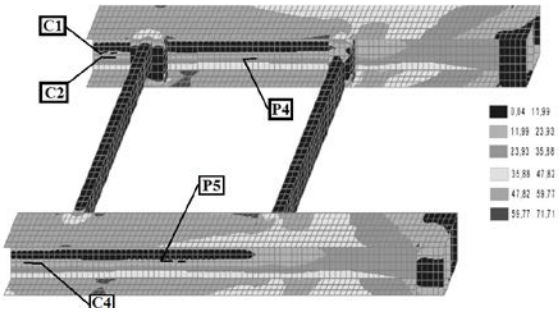


Fig. 7. FE-model of the truss of the ballast leveling machine SPZ-5/UA
Рис. 7. КЭ-модель рамы планировщика балластной призмы СПЗ-5/UA

In operating modes the most values of stresses were observed in the places of fastening of lateral and middle ploughs. Exactly the operating mode “D”, which two central ploughs work at, appeared most unfavorable for a structure from between other operating modes. The values of main stress in the mode “D” attained 68 MPa (Fig. 8, b), equivalent stress – 72 MPa, which is considerably below than possible tensions of 155 MPa.



a)



b)

Fig. 8. Equivalent stresses fields in most loaded part of bearing truss: a) static loading mode (MPa); b) working mode «D» (MPa)

Рис. 8. Поля эквивалентных напряжений в наиболее нагруженных участках несущей рамы: a) режим статической нагрузки (МПа); b) рабочий режим «D» (МПа)

By the Branch Research Laboratory of Dynamics and Durability of Rolling Stock of the Dnipropetrovsk National University of Railway Transport named after Ac. V. Lazaryan were conducted working dynamic tests on durability of the experienced machine of ballast leveling machine SPZ-5. The aim of tests were verification of accordance of structure of pre-production model of machine of SPZ-5 and its durability indexes to the requirements of the Requirement specification, normative documents, that determine the terms of safety of motion and work. Working dynamic tests on durability were conducted in obedience to the program-methodology worked out on the basis of the Requirement specification and [8].

The estimation of durability of bearing structure of ballast leveling machine SPZ-5/UA for the working modes conducted by allowable stresses, for a transport mode of loading – by allowable stresses and safety factor of fatigue resistance [9]. The fatigue resistance of bearing truss of the experienced machine is considered provided, if in all range of speeds, for which tested, got values of safety factor of fatigue resistance does not exceed a normative value which concordantly accepted $[n]=1,5$. As a result of processing of experimental data minimum value to the safety factor of fatigue resistance 2,84, that not less normative value. Therewith, as evidently from a Tab. 3 results of FEM-study well conform with the results of working dynamic tests on durability.

Table 3

The safety factor of fatigue resistance of bearing structure ballast leveling machine SPZ-5

Characteristic structure places	FEM-study	Working dynamic tests on durability	Allowable value $[n]$
C1	2,41	2,72	1,5
C2	3,73	3,45	
C4	3,04	2,80	
P4	3,51	4,03	
P5	3,51	4,26	

The results give a right to predict, that bearing structure of ballast leveling machine SPZ-5/UA keeps a considerable reserve of durability. Such results specify on possibility of optimization of structure of bearing truss of the investigated machine.

3.2. Optimization of ballast levelling machine SPZ-5/UA

The simplified FE-model of truss of planer, which is shown on Fig. 9, was created for realization of optimality calculations. The structure of the simplified model was accompanied by the special control calculations with the aim of obtained results, identical to plate model.

Fig. 9. FE-model of the truss of the ballast leveling machine SPZ-5/UA
Рис. 9. КЭ-модель рамы планировщика балластной призмы СПЗ-5/UA

Problem statement of optimization of bearing structure of ballast leveling machine: the area of cross-section of lateral crosstop of truss $\psi_0 = 2Bt + Hd$, cm^2 came forward as objective function. As design variables came forward height H and width B of cross-section of lateral crosstop of truss. There were the imposed stress constraints in this bar $\sigma = [\sigma]$, and also design variable constraints $B \geq 10$ cm, $0 < H \leq 30$ cm. Except that, there was imposed constraint what value of bar thickness less defined value set from the stability condition could not change in obedience to $d \geq 0,7$ cm and $d \geq 0,6$ cm. Thereby, there was the imposed constraint on the value of thickness of shelf $t \geq 1$ cm. As initial design the real design of structure was selected with the next values of design variables and parameters of structure: $H^0 = 30$ cm, $B^0 = 30$ cm, $t = 1,9$ cm, $d = 1,1$ cm from the value of objective function $\psi_0^0 = 147$ cm^2. With the aim of control of work of optimization procedure additional optimization calculations were executed with an initial design which had such values: $H = 20$ cm, $B = 20$ cm, $t = 1,9$ cm, $d = 1,1$ cm.

The cross-beams of truss it was decided to exclude from optimization, as a change of their sizes is inadvisable on the technological consideration.

On Fig. 10 – 12 shown graphs of change of objective function and design variables of problem during optimization of bearing structure of ballast leveling machine SPZ-5 depending on a select initial design.

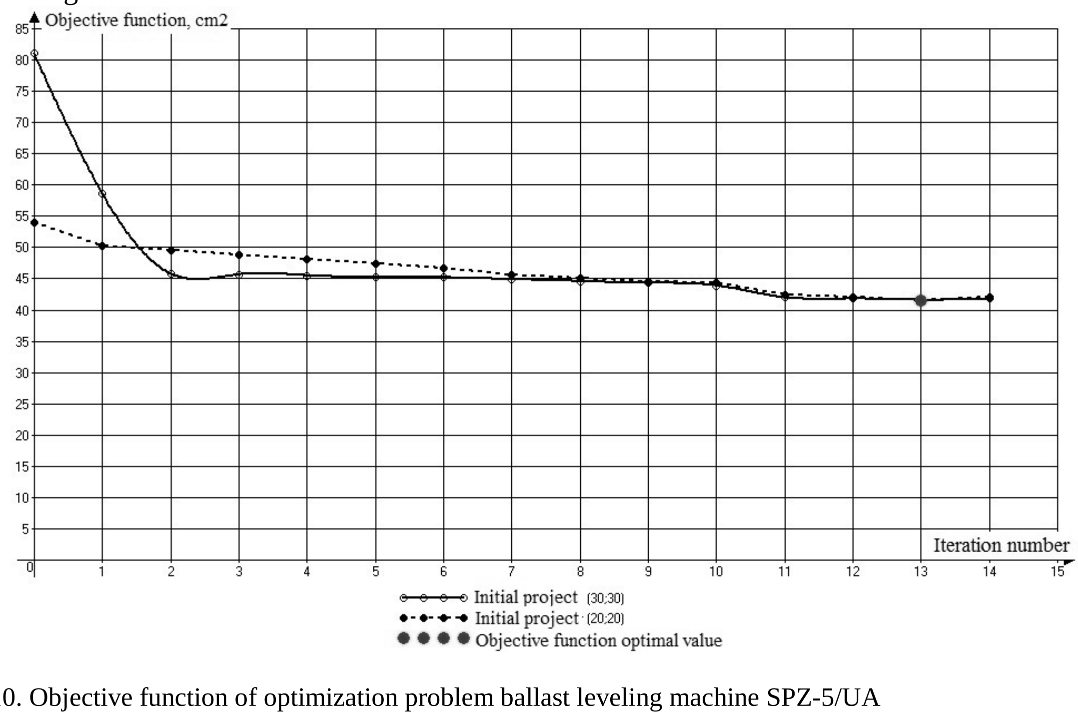


Fig. 10. Objective function of optimization problem ballast leveling machine SPZ-5/UA
Рис. 10. Целевая функция задачи оптимизации планировщика балластной призмы СПЗ-5/UA

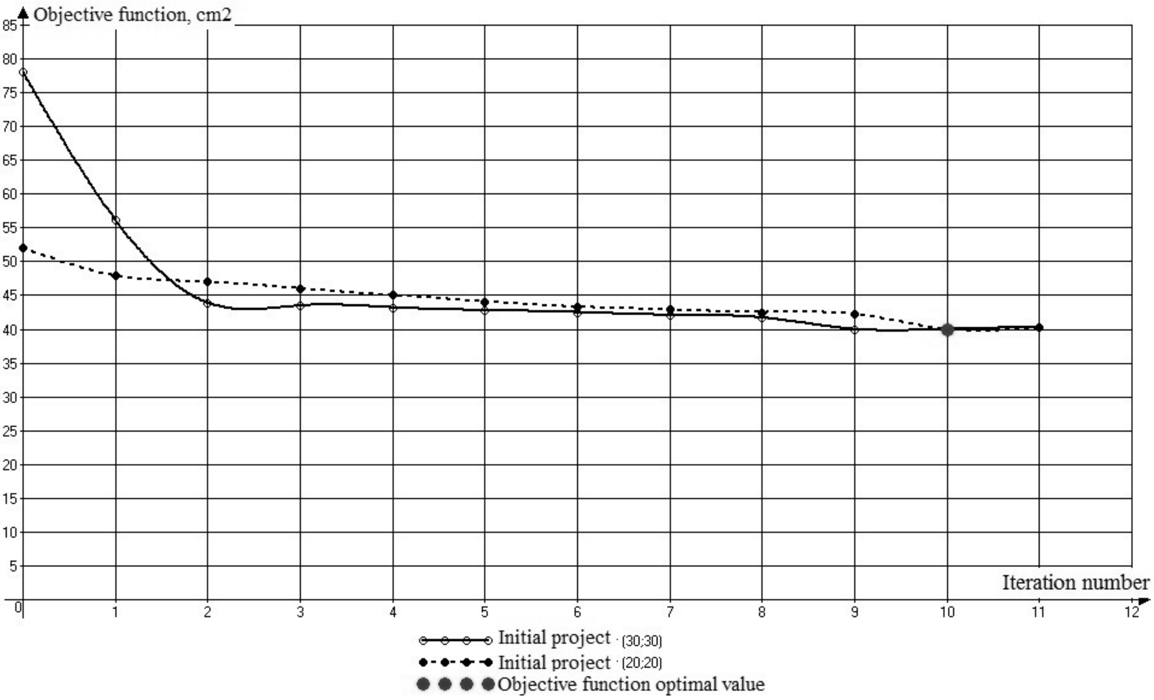


Fig. 11. Height H change under optimization
Рис. 11. Изменение высоты H в ходе оптимизации

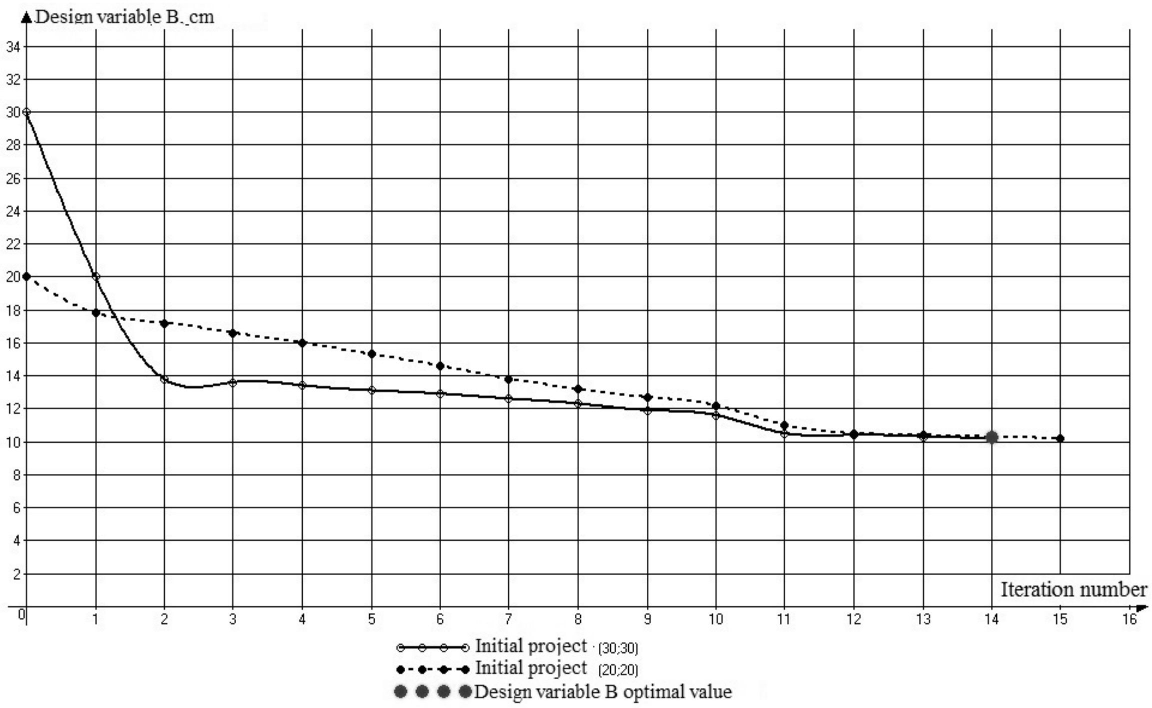


Fig. 12. Width B change under optimization
Рис. 12. Изменение ширины B в ходе оптимизации

As a result of numerical optimization of bearing truss of machine SPZ-5 (Fig. 10) 235% diminishing to the area of cross-section of lateral crosstop (Tab. 4) was done. In a count on metal mass, it had 1101 kg of economy (taking into account that an existent structure has mass of 1529 kg and optimized are 428 kg). It follows to underline that these results are attained at implementation of state variables constraints, in other words real stresses in a structure do not exceed a normative value. Rational design of structure of bearing truss of ballast leveling machine SPZ-5, got as a result of optimization, is accepted on the engineering and technological consideration On Fig. 13 visual comparison of initial (real) is shown and rational designs of cross-sections of longitudinal bar of planer. For the final rational designs stability is provided in obedience to a calculation by БНіП ІІ-23-81*.

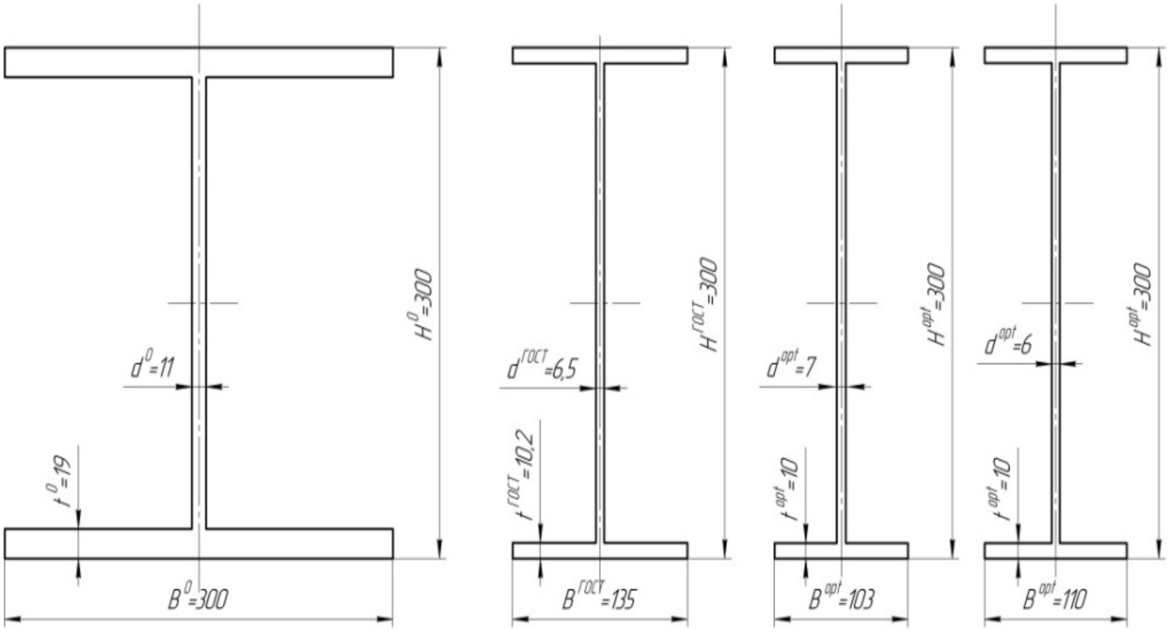


Fig. 13. Real and rational designs of cross-sections longitudinal bar of machine SPZ-5/UA a) real design; b) double-T №30 GOST 8239-89;c) rational design with $d = 7$ mm; d) rational design with $d = 6$ mm

Рис. 13. Реальный и рациональные проекты поперечного сечения продольной балки машины СПЗ-5/UA a) реальный проект; b) двутавр №30 ГОСТ 8239-89; c) рациональный проект с $d = 7$ мм; d) рациональный проект с $d = 6$ мм

For the rational bearing structure of the investigated machine the estimation of durability was executed on the criterion of possible stresses and criterion to the safety factor of fatigue strength. The results give a right for assertion what the bearing structure of ballast leveling machine SPZ-5/UA is optimized keeps a sufficient reserve of durability.

Table 4

The results of optimization of the bearing structure of the ballast leveling machine SPZ-5/UA

	Real design ($d = 1{,}1$ cm, $t = 1{,}9$ cm)	Double-tee №30 GOST 8239-89 ($d = 6{,}5$ cm, $t = 1{,}02$ cm)	Rational design ($d = 0{,}6$ cm, $t = 1$ cm)	Rational design ($d = 0{,}7$ cm, $t = 1$ cm)
H^{opt}, cm	–	30		
B^{opt}, cm	–	13,5	11,0	10,3
W_z, cm^3	1612	465	382	374
σ, MPa	72	147	155	155
$[\sigma]$, MPa	155			
ψ_0^{opt}, cm	147	46,5	40,0	41,6
$\Delta\psi_0$, %	–	216	268	235

4. CONCLUSIONS

In the paper on the basis of the conducted theoretical and experimental researches are offered solution of actual scientific and technical problem on the improvement of technique of designing bearing structures of track machines bodies. Next new results obtained in the paper:

1. Numerical optimization procedure of bearing structures of track machines, that is based on the general use of FEM and one of widespread optimization methods – Gradient Projection Method;
2. Approbation of the offered numerical optimization procedure on the number of problems of optimization of structures similar to the widespread variants of implementation of bearing structures of modern track machines, in particular 7-bar and 6-bar trusses;
3. Research of number of mathematical aspects of the use of the offered numerical optimization procedure, in particular research of procedure algorithm convergence;
4. Research of deflected mode of bearing structures of ballast leveling machine SPZ-5/UA. Justification of necessity of realization of optimization of bearing structures of bodies of the selected machines;
5. Rational design of bearing structure of ballast leveling machine SPZ-5/UA, done as a result of optimization researches which were conducted by means of the numerical optimization procedure offered in paper;
6. Research of deflected mode of the offered rational bearing structure of ballast leveling machine SPZ-5/UA by an analytical way (FEM-study) on the action of the operating loading.

Results done in paper found the use on Public Corporation “Kakhovka plant of electric welding equipment” (KZESO) and in Senior management of track facilities of “UZ” at improvement of bearing structure of body of ballast leveling machine SPZ-5/UA.

Bibliography

1. Haftka R.T., Gurdal Z.: *Elements of Structural Optimization.* Springer, 1992.
2. Spillers W.R., MacBain K.M.: *Structural Optimization.* Springer, 2009.
3. Кострица С.А.: *Применение МКЭ к задачам оптимального проектирования несущих конструкций подвижного состава железнодорожного транспорта.* Вісник Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна, 2003, № 1, с. 127-129.
4. Bathe K.J., Wilson E.L.: *Numerical Methods in Finite Element Analysis.* Prentice-Hall, 1976.
5. Соломонов С.А.: *Путевые машины.* Желдориздат, Москва, 2000.
6. *Машины путевые. Нормы и требования безопасности, эргономики, санитарно-гигиенические и природоохранные. Основные положения. РД 32.65-96* / ВНИИЖТ МПС РФ, Москва, 1996.
7. *Нормы прочности металлоконструкций путевых машин. ОСТ 32.62-96* / ВНИИЖТ МПС РФ, Москва, 1996.
8. *Система испытаний подвижного состава. Организация и порядок проведения приёмочных и сертификационных испытаний тягового подвижного состава. ОСТ 32.53-96* / ВНИИЖТ МПС РФ, Москва, 1996.
9. Timoshenko S.P.: *Strength of materials*: part II. D. Van Nostrand Company Inc., 1947.
10. Кострица С.А.: *Дослідження напружено-деформованого стану несучих елементів конструкції планувальника баластної призми СПЗ-5/UA* / С.А. Кострица, Б.М. Товт. Вісник ДНУЗТу, 2011, №37.
11. Кострица С.А.: *Чисельна реалізація методів математичного програмування в задачах оптимального проектування механічних конструкцій.* С.А. Кострица, Б.М.Товт. Вісник ДНУЗТу, 2009, №30, с. 150-154.

Received 28.03.2011; accepted in revised form 15.07.2012