19. Sokolov A. D. Lightweight retaining walls with ribbed pressure face // Transport construction. 2006. Issue 8. P. 20–24.
20. Measurement of the spreading of the backfill and pressure on the bottom of the embankment in the port of Hakata (Japan) // Pros. Harbour Engng. 1964. Issue 40. P. 4756–4775.
21. RD 31.31.27-81. Guidelines for the design of marine berthing facilities. Moscow: Mortekhinformreklama, 1984. 399 p.
22. Slobodyanik A. V. The calculated substantiation of methods of technical operation of water transport facilities of sheet walls of increased rigidit // News of Odessa National Marine University. 2009. Issue 26. P. 118–131.
23. Slobodyanik A. V., Honeliya N. N. Results of studies of the lateral pressure of the backfill soil on a thin retaining wall // Budivelni konstruktsiyi. 2016. Issue 83. P. 397–402.

UDC 539.3
DOI: 10.15587/1729-4061.2018.120547

THIN-WALLED STRUCTURES: ANALYSIS OF THE STRESSED-STRAINED STATE AND PARAMETER VALIDATION

M. Tkachuk
Doctor of Technical Science, Professor, Head of Department*
E-mail: tma@tmm-sapr.org
M. Bondarenko
Junior Research assistant*
A. Grabovskiy
PhD, Senior Researcher*
A. Vasiliev
PhD*
R. Sheychenko
Chief designer of the tank-car project**
R. Graborov
Head of group of technical settlement**
V. Posohov
Senior Lecturer
Department of Repair and operation of cars and military vehicles
National academy of the National guards of Ukraine
Zakhysnykiv Ukrainy sq., 3, Kharkiv, Ukraine, 61001
E. Lunyov
Manager
JSK "ARGUS-Personnel"
Sichovyh striltsiv str., 3, Kyiv, Ukraine, 04053
A. Nabokov
First deputy director
Dnipropetrovsk Pedagogical College
Polia ave., 83, Dnipro, Ukraine, 49000
*Department of Theory and Computer-Aided Design of Mechanisms and Machines
National Technical University "Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
**JSC "Science Engineering Center UK "RailTransHolding"
Volhohradska str., 24, Mariupol, Ukraine, 87502

Розроблено підхід до обґрунтування технічних рішень для тонкостінних машинобудівних конструкцій. Задача розглядається у просторі узагальнених параметрів, які об’єднують проектні й технологічні чинники та умови експлуатації. У сформованому параметричному просторі будується апроксимована поверхня відгуку. На додаток вводяться критеріальні та обмежувальні залежності. Після цього проводиться пошук оптимуму функції якості досліджуваної конструкції

Ключові слова: тонкостінна машинобудівна конструкція, напружено-деформований стан, поверхня відгуку, інноваційний виріб

Разработан подход к обоснованию технических решений для тонкостенных машиностроительных конструкций. Задача рассматривается в пространстве обобщенных параметров, которые объединяют проектные и технологические факторы и условия эксплуатации. В сформированном параметрическом пространстве строится аппроксимированная поверхность отклика. В дополнение вводятся критериальные и ограничительные зависимости. После этого проводится поиск оптимума функции качества исследуемой конструкции

Ключевые слова: тонкостенная машиностроительная конструкция, напряженно-деформированное состояние, поверхность отклика, инновационный продукт

1. Introduction

Modern industry, transport and service sector are facing these days ever growing demand for innovative engineering solutions. Therefore the machine-building companies are inevitably shifting their focus towards development, pre-production and manufacturing of such products. A substantial part of such activities is related to thin-walled machine

© M. Tkachuk, M. Bondarenko, A. Grabovskiy, A. Vasiliev, R. Sheychenko, R. Graborov, V. Posohov, E. Lunyov, A. Nabokov, 2018

building structures (TWMBS), as long as they provide a rational weight to strength ratio.

At the same time, many products must conform to rather strict official rules and regulations. This applies, in particular, to aircrafts, naval vessels, railway rolling stock, lifting equipment, conveyors, pressure vessels, chemical plants, equipment for agriculture sector. These requirements are aimed primarily at ensuring safe operation.

The regulated quantities are the stresses acting in structural elements, limiting displacements (deflections), durability (the number of working cycles before losing load bearing capacity), etc. Accordingly, design development relies on well-established analysis techniques and traditional technical solutions. As a result, the products made by different manufactures, created at different times on demand of different customers bear the burden of well-established design and technology. Any deviation from these "pattern" solutions is met with resistance from regulators, from consumers, from manufacturers, and from designers.

Despite the current practice which promotes design development as duplication of existing analogues, there is also the opposite trend, which is caused by the common endeavor for progress, even in conservative areas, as well as by economic considerations. This can be well observed for freight railway wagons. Their axial load with cargo is typically restricted to 23.5 tons, 25 tons, 27 tons, depending on the country or region. Accordingly, the less the tare weight, the larger is thy cargo weight. On the other hand, reduced mass usually leads to increased operating stresses, which at some point violate regulatory requirements. Therefore, there is a natural contradiction between the capabilities of existing techniques in justifying technical solutions in terms of strength and other criteria, on the one hand, and the needs of machine building for innovative products, on the other. This is especially relevant for thin-walled machine building structures.

Moreover, many consumers of innovative products set additional requirements for acquired products that concern extended durability, improved performance efficiency, intensity of operating regimes or load capacity. Thus, new approaches that would take into consideration these additional factors are needed for developing new design solutions.

2. Literature review and problem statement

Contemporary technical literature pays a lot of attention to structural and parametric optimization. In order to solve a given task, software complexes for finite element analysis and various optimization techniques have been employed [1, 2]. In particular, a strategy of evolutionary modeling has been widely used [3]. The main difficulty in this case is in fact that the resulting structures might turn to be not suitable for manufacturing with existing industry. Thus, another group of references, which are obviously not less relevant, includes the works concerning adaptation of optimization tools to industrial conditions [4].

Justification of technical solutions for machine building structures, including thin-walled ones, involves various optimization procedures. They introduce into consideration the following parameters: objective function *f*, project variable *p*, operator *y*, variables of state *u*, and constraints *H*(*u*, *p*, *f*) [5, 6]. Then the optimization problem can be stated as:

$$p^{*}: f(p) \rightarrow \min,\ \ y(p,u)=0,\ H(u,p,f) \geq 0. \tag{1}$$

The response function (graphically viewed as a response surface) serves as a mathematical model for the optimization procedure.

In some cases, the nature of relation between response variable *y* and controlling variable *p* can be known precisely, for example, it can be based on engineering, chemical or physical principles. Then one can constitute a model in the form $f=g(p_1, p_2,..., p_k)+\varepsilon$, where ε is the "error margin" in the system. Such type of constitutive relation is often called a mechanistic model. However, in case of design optimization in machine building this principle is not directly applicable since initially there is no working method for evaluation of ε.

When a mathematical model, that is, the response function, is constructed, there is a problem of choice of optimization method [7, 8]. As far as non-linear functions are concerned there is a great variety of methods locating extrema, given the complexity of the search [7]. However, most of these methods can be characterized as the methods of iterative improvement of the initial solution. The essence of most methods of non-linear programming is in the motion in space to an optimum first from the original, and next from the intermediate state of the variable of optimization problem to the subsequent state at a certain step.

Thus, by its very nature, the applied problems of solution justification for innovative products tend to be subjected to different kinds of "variability". It is important to note that such variability is a natural property of the applied problems of parametrical structural synthesis of innovative TWMBS. Traditional approaches, in contrast, tend to focus on solving classical nonlinear programming problems with an objective function, constraints and a process or state model of process or state that are clearly set. Therefore, the traditional statement usually contradicts the nature of emerging applications. When such statement is imposed with actual conditions of development of innovative TWMBS (lack of time, funds, organizational difficulties with supplies and components, etc.) the merit of strict solution of a formal optimization problem (1) gets lost.

Thus, designers of innovative products are given the task of devising not an optimal structure, but rather a "robust" design, capable of maintaining the required high technical-economic characteristics with any change of the influencing factors (design parameters) over a certain range of variation in *p*, *f*, *H*. With that in mind, problem (1) can be replaced with its approximated variant:

$$p^{**}: f^{\wedge}\left(p^{\wedge}\right) \rightarrow \min,\ \ y^{\wedge}\left(p^{\wedge},u^{\wedge}\right)=0,\ \ H^{\wedge}\left(u^{\wedge},p^{\wedge},f^{\wedge}\right) \geq 0. \tag{2}$$

In (2), index "^" refers to certain approximations of appropriate quantities and functions in (1).

It is only natural that the notion of a "certain approximation" introduces an element of arbitrariness, since it implies selection of some technique for approximated notation of *p, f, H, y, u*. However, it can be argued that such approximations are inevitable, either explicitly or implicitly, in problems solved numerically [9]. In addition, any technical task in practice does not usually have a the unique solution, but rather a set of solutions, obtained, for example, by various designers from a common starting statement. And the main problem is not in fact that the solution p^{**} is the only one, but that there is a whole lot of them out there. The key is to choose those approximations that make it possible to clearly and quickly find the robust solution. We should also note that in many cases innovative products have good original approximations – technical solutions for traditional products developed earlier that had been operated for a long time. This is an additional argument in favor of the proposed approach.

Some of the arguments considered above have been already outlined in several earlier papers [5, 6], first of all, an approach to the construction of variative mathematical and numerical models of the investigated processes and states. Thus, it seems appropriate to develop such types of approaches in order to solve applied problems of justification of technical solutions when creating innovative thin-walled machine building structures. They are needed to resolve difficult issues while justifying parameters for innovative TWMBS, specifically, the variability of conditions of optimization problems and the complexity of building variative models of the examined processes and states.

3. The aim and objectives of the research

The aim of present work is to develop methods for justification of design parameters of innovative thin-walled machine building structures. The developed approach in contrast to well-established methods should take into consideration variability of loading conditions of newly designed products along with multiple criteria (both technical and economic) and regulatory constraints. This would make it possible to abstract from certain patterned solutions and overcome the bar that defines the product as innovative.

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

1. An adaptation of the technique of generalized parametric modeling for a justification problem for technical solutions of innovative thin-walled machine building structures. This would provide for the variability in models of the process and state analysis in the examined TWMBS, criterial characteristics, and constraints.

2. Development of a method for the estimation of actual response surface by an approximated analog. In contrast to the technology of a “black” or a “white (transparent) box”, an alternative technology of a “gray box” is applied to solving the posed problem. It implies gradual stepwise refinement of the approximated response surface relative to the actual one in proportion to a current approximation of the solution, which would dramatically reduce computational costs while maintaining the required accuracy.

3. Application of an alternative, compared to conventional, method for the estimation of sensitivity of characteristics of thin-walled machine building structures to the variation in their parameters by calculating these sensitivities for finite-difference ratios. In this case, it is proposed not to look for a more precise description of response surface in the local vicinity of one or another point of the parametric space, but rather estimate “global” trends in behavior of a given surface. Next, in the selected region of parameters, instead of the actual response surface, we shall employ an “approximated analog”. This makes it possible to avoid consideration of local attributes of behavior of the actual response function. We aim to achieve a double effect:

1) the “numerical” one implies eliminating potential multiplicity of local extrema;

2) the “applied” one implies getting rid of the redundant process of searching for a “real” optimal solution, which, owing to the “blurred” actual real response surface, might prove to be far from that.

4. Solution of several applied problems of design justification of technical solutions for innovative TWMBS by the criteria of durability and strength.

4. Methods of analysis and parameter synthesis of thin-walled machine building structures

In order to analyze the stressed-strained state (SSS) of innovative thin-walled machine building structures, relations of elasticity theory, theory of plates, shells, and rods, as well as a numerical finite-element method (FEM) are applied [9]. The formation of geometrical shape of the considered TWMBS was performed employing the methods of solid-body and surface modeling. For a variable change in the structure and dimensions of the investigated objects, we adapted and developed the method of generalized parametric modeling in relation to innovative TWMBS.

Numerical study was performed in the environment of software framework ANSYS (National Technical University “Kharkiv Polytechnic Institute” and Scientific-Engineering Centre of the company “RailTransHolding”, Mariupol, Ukraine).

4. 1. Construction of parametric models of the stressed-strained state of thin-walled machine building structures

Ensuring strength characteristics of innovative thin-walled machine building structures, as was noted above, implies multiple options of computational analysis of their stressed-strained state. In this case, it is important to take into consideration the logic, noted above, in terms of multiple-choice loads, changeability of requirements, variability of the applied methods and models, augmented by the uncertainty of structural and parametric solutions. Thus, traditional approaches may prove to be inapplicable when validating design solutions for innovative products, because, by relying on standard criteria, regulatory loads and unambiguous procedures, one restricts the set of considered design options. In this regard, it is required to develop such approaches that ensure variability of physical, mathematical and numerical models at the stage of SSS analysis for the thin-walled machine building structures. The specified requirements are satisfied by the advanced parametric modeling approach described below.

At present, they design and manufacture a large number of innovative thin-walled machine building structures exposed to operating conditions, which vary very much depending on various factors. In this case, it is important that different factors affect load intensity, load-bearing capacity, and durability in a variety of ways. Thus, the action of wind loading results in the stochastic distribution of aerodynamic forces. Loads that occur at motion of vehicles along automobile roads and railways have a distribution of similar nature, although their characteristics and the nature of their occurrence are different from the above-mentioned. The same arguments apply to technological, contact, seismic and other loads.

The established practice of machine building structures analysis in this case consists in identification of several types of characteristic loads: extremal loads, transient loads that are varied within certain range according to some law of distribution etc. Afterwards the evaluation is performed for each type of loading modes together with establishing certain criterion and constraint (for strength, stiffness, mass, etc.).

The main shortcoming of the above-specified approaches is that they are connected to a certain set of specific parameter values. This is the most significant obstacle in the synthesis procedure for rational parameters of the designed thin-walled machine building structures. It should be noted that the variation in the same parameters differently affects a change in their optimal values for various criteria and constraints (depending on the type of analysis, regime, process, etc.). If we take into consideration, in addition, that the resulting response surfaces (that is, the values of some characteristics, derived from calculations, and important in terms of the designed structure operation) in a general case are described by the nonlinear functions of parameters, we ultimately obtain a very complicated multi-layered synthesis task. In turn, this dramatically reduces effectiveness of solving the problems on justification of rational parameters for thin-walled machine building structures. This shortcoming is further exacerbated by the fact that, as was already stated, the criteria themselves, as well as constraints and the structure of the investigated design, can be changed even during execution of the project development. As a result, the obtained solutions to the problems of synthesis lose their practical significance, which means that computational, financial and time resources are wasted.

In order to resolve the specified contradiction, we propose several ways. The easiest, though cost-inefficient, implies preliminary study into as many as possible variants of design solutions and structural parameters. This task, because of the upsurge in the array of information, is often not feasible even when large computational resources are available. Such a technique is justified either in the early stages of design in order to choose conceptual solutions, or for structures with a minimum quantity of varied parameters. The second possible way for solving a set task implies application of known, or new and improved, optimization methods [8, 10, 11]. Algorithms that implement optimization are now embedded in contemporary packages for running a finite element analysis and, for certain types of structures, they produce satisfactory results. However, as noted above, at a multiple change in the criterial functions the results obtained may vary dramatically, for example by leaps, at continuous variation of certain parameters. This can be predetermined by both the form of an objective function, as well as constraints, and special features of the implemented physical-mechanical process or state. An additional challenge in this case is the implementation of criterial functions that differ from those traditionally present in the engineering calculations (for example, economic, technological, etc.).

The technologies reviewed here can be described as procedures of a "white (transparent) box" and a "black box". In the first case, at high costs, one obtains information about the behavior of criterial functions over a wide range of variation in parameters. In the second case, the knowledge about a function is limited to the calculation of certain characteristics after solving certain problems on the analysis of the implemented process or state. As it is often observed in other cases, these extreme, in a sense, approaches possess many "innate" drawbacks that naturally follow their nature. In order to overcome negative aspects inherent to the above- mentioned approaches of a "black box" and a "white (transparent) box", it is required to develop alternative-compromise methods.

Alternatively, we propose a method for the substantiation of rational parameters and design solutions for thin-walled machine building structures for certain criteria (for example, reduction of mass, decrease in stress, reduction of vibrations, etc.), considering gradually localized linear approximations of criterial magnitudes for the changed parameters. Linearized approximations are understood as the approximation in a certain region of the field of variation of parameters for the exact response surface. Localization refers to the special feature of the linearization procedure that assumes that the dimensions and location of the field within which the approximation is performed may change when searching for a solution.

In this case, linearization is a compromise variant of approximation (compared to the algorithm of a "white (transparent) box", which "shades" actual behavior of the described function. The procedure of localization, a compromise as well, yields the opposite effect.

The sequence of approximated functions, obtained in the end, reflects a transition from an "almost black box" to an "almost white (transparent) box". If we call this approach a "grey box" method [12], then for such a compromise algorithm there is a problem on developing an alternative traditional technique for the linearization of criterial functions. Such a method requires relative simplicity, accuracy, and universality.

Consider optimization problem (1) in a somewhat modified form:

$$I(H,u,p)\to \min;\ \ H(u,p)\geq H^{*};\ L(u,f,p,H)=0, \qquad (3)$$

where I is the function of quality (mass, stress, etc.); u is the variable that describes a certain state or a process in the investigated object; H^{*} are the constraints for technical specifications of H; L is the operator of the problem on analysis of a physical-mechanical process or a state, which is implemented during operation of a structure; f are the external loads; P is the set of generalized parameters p.

Generalized parameters denote a set of magnitudes, structures, forms, distributions, which are characterized by the following:

– they fully define a mathematical model of the investigated process;

– they do not change when solving a problem on analysis;

– they are variable when solving a problem on synthesis.

Such an approach is consistent with the one declared in paper [12] and allows us to extend a technology of traditional operation with parameters to the set of generalized parameters.

If we consider thin-walled structures, operator L is defined on manifold R in a three-dimensional space. This manifold is the combination of middle surfaces of shells, plates and rods' lines that make up a 3-D region Ω, taken by the investigated object:

$$\Omega=R\times t, \qquad (4)$$

where t is the thickness of the plate, shell (or cross-section), which are the generalized parameter $t(Z)$ distributed by points Z of manifold R.

Thus, at the initial stages of project research, there are two basic tasks set and solved:

1) determining the structure (“skeleton”) of a thin-walled structure R;

2) substantiation of rational thickness distribution, as well as the shape and size of cross-section $t(Z)$.

In this context, problem 1) is a structural task, 2) – a parametric optimization task with $t(Z)$ being a distributed generalized parameter.

In line with papers [6, 12], it is possible to transform the original continual problem statement (3), (4) into a discrete one. To do this, one should introduce, in addition to the discretization of u, f, L, the discretization of the set of generalized parameters P. Bearing in mind that we shall subsequently consider a problem of parametric optimization of $t(Z)$, we should confine ourselves to the discretization of this distributed parameter. The resultant discretization problem of distributed parameter t can be linked to the discretization of analysis problem (the last ratio in (3)). If one applies FEM for this purpose [9], then the problems of “physical” and “parametric” discretization will be naturally connected. In this case, the constructed FEM ratios will automatically include parameter $t(Z)$ in the form of thickness distribution of finite elements (FE), areas and moments of inertia of the cross-section either for the finite elements or for the finite-element grid nodes.

In particular, if we represent R in the form of combination (ensemble) of finite elements R_e:

$$R=\bigcup_e R_e,\quad e=1,\ldots N_e, \tag{5}$$

then it is possible, in the simplest case, to approximate t by piecewise-constant functions:

$$t\big|_{R_e}=t_e=\text{const}. \tag{6}$$

Then, without violating standard procedures of the finite-element modeling, it is possible to obtain implicit or explicit dependences of the magnitudes that define the physical-mechanical properties of the examined object on a set of parameters (6). Thus, if we look at static and dynamic stressed-strained state of a thin-walled structure, the range of its own frequencies ω_i and critical efforts λ_i (from the conditions for stability loss), then we come to the appropriate systems of equations:

$$K\cdot u=f, \tag{7}$$

$$M\ddot{u}+C\dot{u}+Ku=f(t), \tag{8}$$

$$Det(K-\omega^2 M)=0, \tag{9}$$

$$(K+\lambda_i S)\psi_i=0, \tag{10}$$

where K, M, C are the matrices of stiffness, mass and damping of the finite-element ensemble that simulates original thin-walled structure; u, f are the vectors of nodal loads and external forces; S is the matrix of initial stresses; ψ_i are the i-th forms of stability loss.

Paper [12] demonstrates that dependences

$$K=K(t_e),\quad M=M(t_e),$$

$$C=C(t_e),\quad f=f(t_e),\quad S=S(t_e) \tag{11}$$

can be represented in the vicinity of some base point $t^{(0)}$ with a sufficient degree of accuracy in the linear form:

$$\left.\begin{array}{l} K(t)\approx K(t^0)+K'(t^0)\cdot\alpha;\ M(t)\approx M(t^0)+M'(t^0)\cdot\alpha; \\ C(t)\approx C(t^0)+C'(t^0)\cdot\alpha;\ f(t)\approx f(t^0)+f'(t^0)\cdot\alpha; \\ S(t)\approx S(t^0)+S'(t^0)\cdot\alpha, \end{array}\right\} \tag{12}$$

where

$$\alpha=\left\{\left(t_1-t_1^{(0)}\right)/t_1^{(0)},\left(t_2-t_2^{(0)}\right)/t_2^{(0)},\ldots,\left(t_{N_e}-t_{N_e}^{(0)}\right)/t_{N_e}^{(0)}\right\}^T,$$

$$t^{(0)}=\left\{t_1^{(0)},\,t_1^{(0)},\ldots,t_{N_e}^{(0)}\right\}^T,$$

$$t=\left\{t_1,t_2,\ldots,t_{N_e}\right\}^T$$

and matrices $K, M, C, S, K', M', C', S'$, as well as vectors f, f', do not depend on t.

In this case, we argue about validity of the linearization of properties of a finite-element model (FEM) of the examined object near some point $t^{(0)}$ in a multidimensional parametric subspace, which discretizes a continuously distributed parameter $t(Z)$. Here α is the array of relative (dimensionless) magnitudes that characterize the degree of change in the thickness of separate finite elements.

Substituting representation (12) in ratios (7)–(10) (in line with papers [12]), one can argue that the solutions to problems (7)–(10) at a variation in the assay of parameter t (and hence, α), can be represented with a reasonable degree of accuracy in the form of a linear dependence on the degree of their variation. In other words,

$$u(\alpha)\approx u(0)+\nabla_1(0)\cdot\alpha; \tag{13}$$

$$u(\alpha)\approx u(0)+\nabla_2(0)\cdot\alpha; \tag{14}$$

$$\omega_i(\alpha)\approx\omega_i(0)+\nabla_3^i(0)\cdot\alpha;\quad i=1,2\ldots; \tag{15}$$

$$\lambda(\alpha)\approx\lambda(0)+\nabla_4^j(0)\cdot\alpha;\quad j=1,2\ldots. \tag{16}$$

Here ∇_q $(q=1\div 4)$ are some matrices that correspond to the inverse operators in problems (7)–(10).

Summing up this phase, one can argue that ratios (13)–(16) assign a potential possibility for determining the response of the examined process or state to a change in parameters. At the same time, a question that remains open is the computation of sensitivity matrices ∇_q (q=1÷4) themselves.

Calculating the sensitivity matrices ∇_q produces information needed to approximate the dependence of characteristics of the controlled physical-mechanical process or state on the parameters that are defined by the object of research. Given the linearity of the problem for external influences (“physical” and estimated linearity for a change in parameters in the vicinity of a certain base point), it can be concluded that the criterial magnitudes in (3) are either linear in their structure, or linearized for parameters p (including for $t(Z)$). In this case, problem (3) turns from a problem in a general case of nonlinear programming into a problem of linear programming, which significantly accelerates a solving process. Thus, the main hurdle to accelerating the solving of synthesis problems is the identification of components of sensitivity matrices ∇_q.

Consider solving a given problem without sacrificing generality by using parameters t as an example. In order to solve the problem obtained, one can refer to the methods of perturbation theory. In this case, it is possible to obtain exact expressions for the components of sensitivity matrices ∇_q in the analytical form. However, the accuracy of approximation representations (13)–(16), which hold for infinitesimal α_e, could worsen dramatically at small but finite α_e. Thus, the value of representations (13)–(16) reduces because their accuracy and applicability is limited by infinitesimal neighborhood of base point $t^{(0)}$ of the parametric subspace. This, in turn, nullifies the anticipated benefits of linearization in the context of the approach proposed in the present work. Given this, an alternative technique for calculating the sensitivity matrix components is required. It can be constructed according to the approaches described in papers [6, 12].

Thus, by introducing a certain characteristic magnitude of intensity α_e^* (different in a general case for different finite elements), it is possible to assign a set of the so-called "reference" points:

$$\alpha_\tau^\wedge = \{0,0,...,0,\alpha_\tau^*,0,...,0\}^T, \tag{17}$$

where a non-zero component of array $\alpha_\tau^\wedge$ is only components with number τ. Then, in order to calculate sensitivity matrix components $\nabla_q^{(\phi,\psi)}$, one can employ their finite-difference approximation:

$$\nabla_q^{(\phi,\psi)} \approx [u_\phi(\alpha_\psi^\wedge) - u_\phi(0)]/\alpha_\psi^*,$$

$$(q = 1 \div 4), \quad (\phi,\psi) = 1 \div N_e. \tag{18}$$

Here $u_\phi(\alpha_\psi^\wedge)$ are the "reference" solutions, that is, numerical solutions to (7)–(10) at $\alpha = \alpha_\psi^\wedge$. Ratio (18) is locally (in the extreme case of infinitely small increments of α_e^*) equivalent to sensitivity coefficients, calculated according to perturbation theory. At the same time, by worsening the local representation of ∇_q on average by volume, cut off by the "reference" points, we obtain a more exact correspondence between expressions (13)–(16) and the actual response surfaces in some finite vicinity. In this vicinity rather than in an infinitely small, we find a rational combination of the desired parameters.

Thus, we can conclude that we have obtained a tool for the approximated calculation of sensitivity matrix components, based only on the use of properties of linearity (or possible linearization) of the approximated functions.

Expression (18), given the above considerations regarding the linearity (or linearization), can be also applied to functions I, H:

$$I \approx I(0) + \nabla_I \cdot \alpha^T;$$

$$\nabla_I = \{\nabla_I^{(1)}, \nabla_I^{(2)}, ...\nabla_I^{(N_e)}\}^T;$$

$$\nabla_I^{(\psi)} = [I(\alpha_\psi^\wedge) - I(0)]/\alpha_\psi^*; \tag{19}$$

$$H \approx H(0) + \nabla_H \cdot \alpha^T;$$

$$\nabla_H = \{\nabla_H^{(1)}, \nabla_H^{(2)}, ...\nabla_H^{(N_e)}\}^T;$$

$$\nabla_H^{(\psi)} = [H(\alpha_\psi^\wedge) - H(0)]/\alpha_\psi^*. \tag{20}$$

As a result, the initial problem of nonlinear programming (3) is reduced to the problem of linear programming

$$\nabla_I \cdot \alpha^T \to \min, \quad \nabla_H \cdot \alpha^T \geq H^* - H(0). \tag{21}$$

In this case, the arrays of sensitivity coefficients ∇_I, ∇_H are calculated in line with procedure (19), (20), which is an alternative to traditional. The degree of "transparency" of the conventional "grey box" changes along with a change in the degree of localization, determined by the values of α^*.

To solve the problem obtained, it is possible to apply one of the many known methods [13].

Upon performing a series of linearization described above, we consequently obtain a sequence of linear programming problems (21) with adjustable position of base point $t^{(0)}$ and converging range of change in α^*. This means that, when approaching the described solution (21) in steps, it is possible to simultaneously specify the nature of behavior and solution to the analysis problems (13)–(16), as well as values of sensitivities (18)–(20).

It is only natural that each of the steps and stages in solving a set problem implies a certain margin of error caused by the character of behavior of approximation functions, the form of the obtained dependences, as well as by a step of finite-difference approximations. Instead of assessing the error introduced at each stage, it is proposed to solve a series of test problems for separate machine building structures and estimate permissible resulting error for each case and in general.

4. 2. Algorithmization of the proposed methods for thin-walled structures analysis

Upon defining different statements and methods for solving particular problems, there is a need to develop the structure of research aimed at their implementation. Research tools employed in experimental and numerical studies should be combined, first, by a common format for storing the array of primary information, and, second, they should provide for the possibility to modify models of the examined objects.

Thus, for a separate class of structures, we compile its generalized parametric notation [12], which should satisfy the requirement: to be able to construct, based on a specified set of generalized parameters, and unambiguously at that, a model of the examined object in a predefined format. On the other hand, a mechanism should be established that allows for the variation of generalized parameters while maintaining the integrity and consistency of the model. Applying the entire arsenal of the existing systems CAD/CAM/CAE (Creo, Catia, ANSYS, Abaqus, etc) does not meet all the requirements for the tools and possibilities of research. However, ignoring the capabilities of these specialized software systems is impractical, particularly in relation to automated creation of FEM, computation, and post processing.

Given all designated arguments, the following structure of research was proposed (Fig. 1).

The proposed structure of research combines many of the advantages of universal and specialized, public and private, automated and manual systems, being largely devoid of their shortcomings. The examples that follow demonstrate possibilities of a given system for separate objects and types of problems.

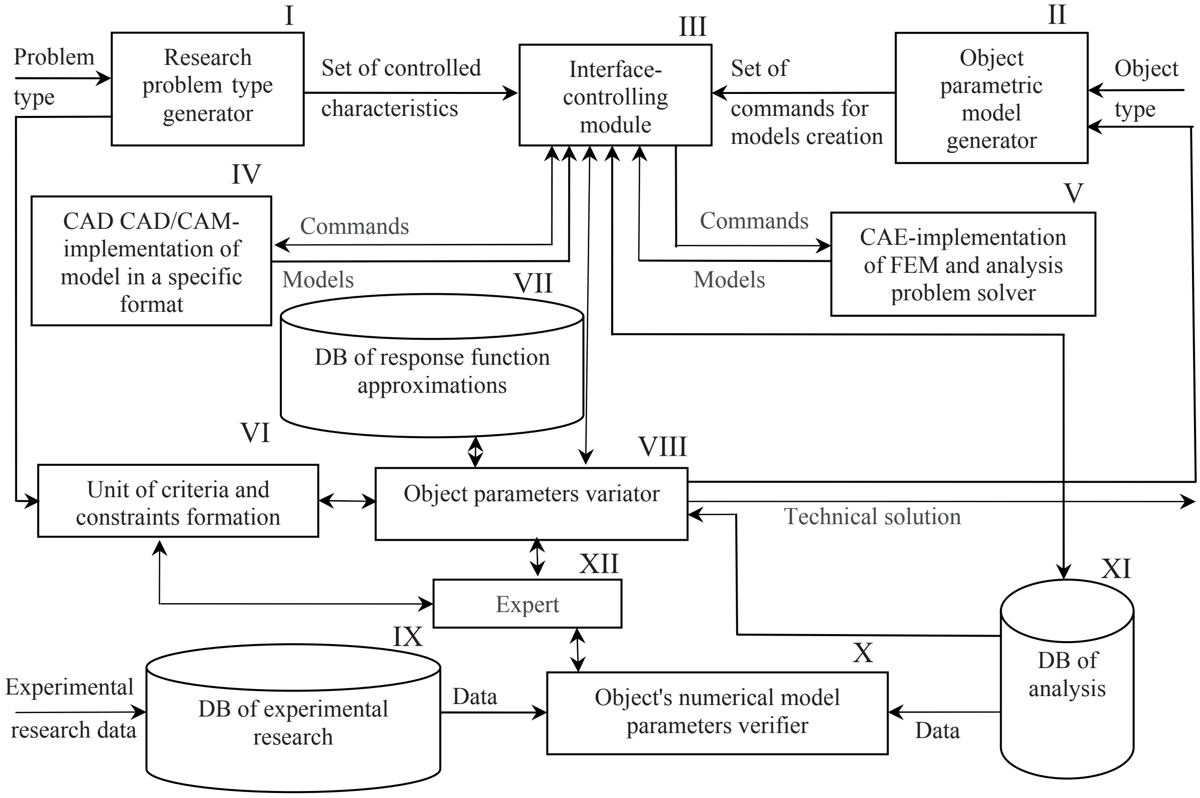


Fig. 1. Proposed structure of research into thin-walled machine building structures

5. Application of the proposed approach to solving test problems

Demonstration of possibilities of the proposed approaches is illustrated using a number of innovative thin-walled machine building structures as an example.

Problem No. 1. Determining the parameters of a bus body structural elements that ensure the required strength and rigidity.

Problem statement simulates testing the force structure of a passenger bus at a special test set-up, which is a requirement of the FMVSS safety standards, applicable to vehicles of a given type. The design scheme of load application takes into consideration the impact of a flat plate on the vehicle roof, Fig. 2. Research was conducted on a rod model with respect to geometrical, physical and structural non-linearities [14].

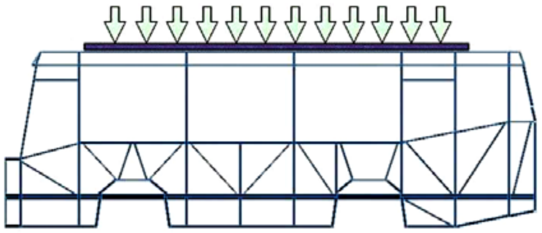
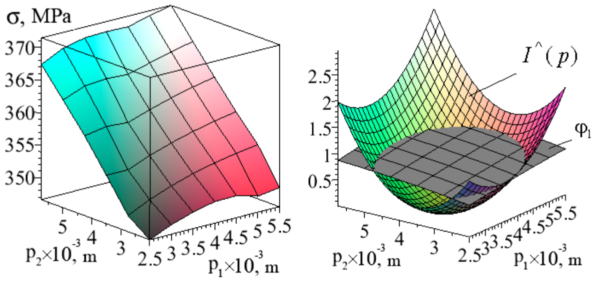


Fig. 2. Schematic of loading the structure

Research procedure implied a variation in the thicknesses of racks p_1 and roof bars p_2. The choice of optimum values for these parameters was based on assessing the implications of equivalent stresses that occur in the structure (Fig. 3, *a*) and the mass of the structure ($m(p) \to \min$ at constraints $\sigma \leq [\sigma]$) taking into account the "cost" of design-technological changes

$$I = \sum \gamma_i \left(p_i - p_{i_0} \right)^2 .$$

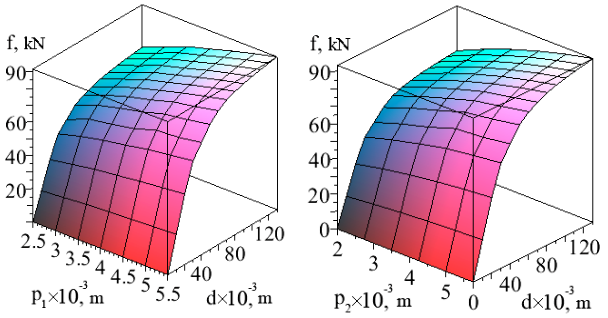
Here γ_i are some weight coefficients that "evaluate" the cost of changing a separate design-technological parameter. Fig. 3, *b* shows function $I^{\wedge}(p)=I(p)/I(p_0)$ for a given structure at $\gamma_1=\gamma_2=1/2$ with the constraints for stresses and critical efforts $P_{cr} \leq [P]$ (function φ_1). In addition, we investigated dependences of the emerging reaction in support *f* on the displacments of plate *d* at alternating variation in parameters p_1 and p_2, Fig. 4, *a*, *b* (denoted here as "evolution surfaces").



a *b*

Fig. 3. Problem statement: *a* – response surface of the maximal equivalent stresses by Mises; *b* – form of functions $\hat{I}(p)$ and φ_1

Presented results show that despite a substantial nonlinearity in the model of analysis of SSS, both response surfaces (Fig. 3, *a*) and "evolution surfaces" (Fig. 4, *a*, *b*) have a smooth character. For this reason, in the neighborhood of any point of determining the constructed functions, these functions can be linearized both for the design and the load (performance) parameters. Based on this, the recommendations were prepared for determining technical solutions to the frame of a bus. SSS analysis of the structure with recommended parameters has demonstrated that the structure meets all the requirements for strength and rigidity.



a *b*

Fig. 4. Dependences of the controlled characteristics on parameters: *a* — variation of parameter p_1; *b* — variation of parameter p_2

Problem No. 2. Substantiation of parameters for structural elements of the platform wagon and test loads.

It is required to assess the stressed state of the structure of a platform wagon under the action of vertical forces from the cargo located on the platform in accordance with testing methods for cargo and passenger wagons for durability and performance RD 24.050.37.95. There is also a problem to be solved on the substantiation of tested cargo arrangement scheme during running tests of the platform wagon. The statement of problem in this aspect requires identification of loading modes that, first, can be implemented in practice, second, they create in the force elements of a platform wagon the most unfavorable stressed-deformed state. If the requirements on strength are met in this, the most unfavorable, case, then the strength requirements set by the regulation documents would be satisfied by default.

In the first variant, a vertical load on the wagon tested for static strength is formed by two 20-foot container imitators with a mass of 72 tons. The estimated scheme took this load into account by applying relevant efforts to the surfaces of the fitting supports. The assigned kinematic boundary conditions include fixation to prevent displacements along the *Ox*, *Oy* axes and turning around the *Ox* and *Oz* axes in the region of the calculated model, corresponding to leaning on the support, Fig. 5. The computer model is shown in Fig. 6.

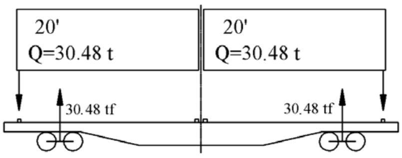
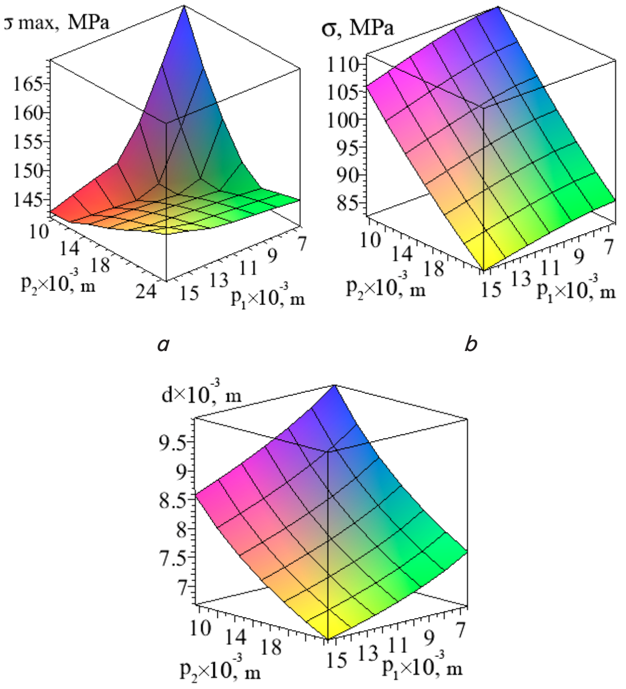


Fig. 5. Scheme of loads and constraints application

To study variation, we selected thickness of the elements of a center girder, which is the most important element in a force structure. Parameters p_1 and p_2 varied over the ranges of 6.5–15.5 mm and 9.5–24.5 mm, respectively, Fig. 7. Displacement and stress response surfaces, constructed based on our calculations, are shown in Fig. 7, *a*–*c*.



a *b*

c

Fig. 7. Magnitudes of the estimated characteristics when changing parameters of the center girder of a platform wagon: *a* — maximum stresses; *b* — stress at point A of the computational model; *c* — maximum displacements

The second variant of loading is the loading when placing a 40-foot container, Fig. 8, *a*. The third variant of the stressed-strained state is the loading with a uniform load of 60 tons for the middle cross-section of longitudinal beams, distributed along a length of 4.3 m, corresponding to the length of the supporting surface of heavy tracked vehicles, Fig. 8, *b*.

In terms of finding unfavorable combinations of loads in a general case of variation in design parameters p_1, p_2, we constructed objective functions $\sigma_{e\,\max}(p_1, p_2, n_v)$. Here n_v is the number of a loading variant. Figure 9 shows a chart of function distribution $\sigma_{e\,\max}(p_1, p_2, n_v)$. One can see that the most unfavorable variant in the examined range of variation in parameters ($p_1>9\cdot10^{-3}$ m, $p_2>18\cdot10^{-3}$ m) is the third variant of loading. In the remaining region of variation in parameters p_1, p_2, the unfavorable one is the first variant of loading.

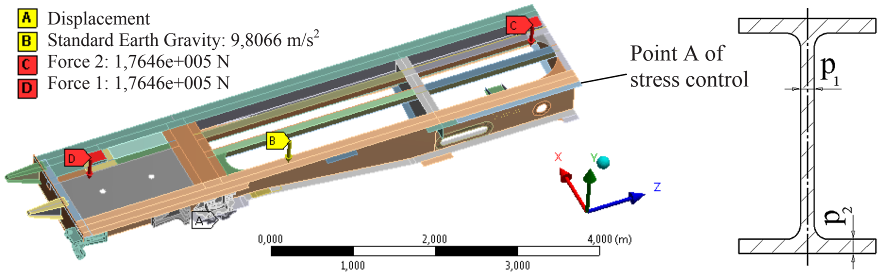


Fig. 6. Computer model (1/4 wagon) and variable parameters of the element of a center girder of platform wagon

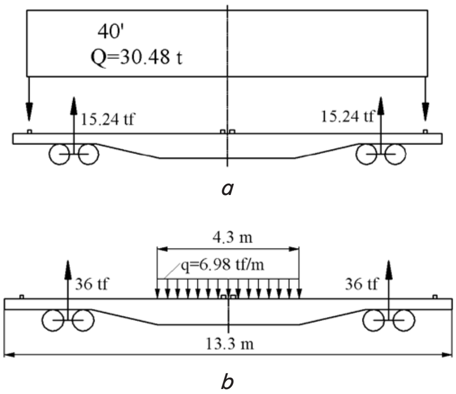


Fig. 8. Loading variants: *a* – No. 2; *b* – No. 3

We shall next consider the third variant of loading as the unfavorable one. In this case, one can notice that the form of $\sigma_{e\,max}(p_1, p_2)$ of distribution σ^N in a general case is greatly affected by the loading variant. For all the investigated combinations of parameters p_1, p_2 it is possible to identify the most unfavorable loading variant. A response function can be constructed from the upper petals of separate surfaces shown in Fig. 9. Thus, it is this variant of loading that must be implemented during numerical study and experimental tests of the platform wagon.

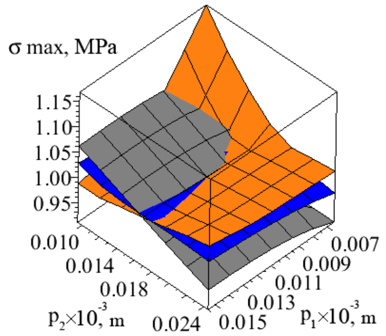


Fig. 9. Functions $\sigma_{e\,max}$, reduced to maximum equivalent stresses at base combination of varied parameters, for the cases of different variants of loads: 🟧 – loading variant No. 1; 🟦 – loading variant No. 2; ▨ – loading variant No. 3

Based on this, we substantiated design, technological and operational parameters for the platform wagon [6].

Problem No. 3. Construction of response surface during optimization of the force structure of a freight semi-wagon.

When working out a scheme of application of loads and constraints, it was assumed that a wagon was loaded with coal "without a hat". It was modeled by applying the thrust forces to the walls of the wagon and vertical forces from the weight of the load. Kinematic boundary conditions are assigned similar to the preceding problem – constraint for displacements along the *Oy*, *Oz* axes, and turns around the *Ox* and *Oz* axes in the region of leaning on the support (Fig. 10).

We varied thickness of a semi-wagon walls (group of parameters p_1) and elements of the center girder (group of parameters p_2). Fig. 11 shows response surfaces, that is, the value of maximum displacements and strains, as well as the mass, respectively, at different combinations of variable parameters related to the values of these characteristics at a basic combination of parameters.

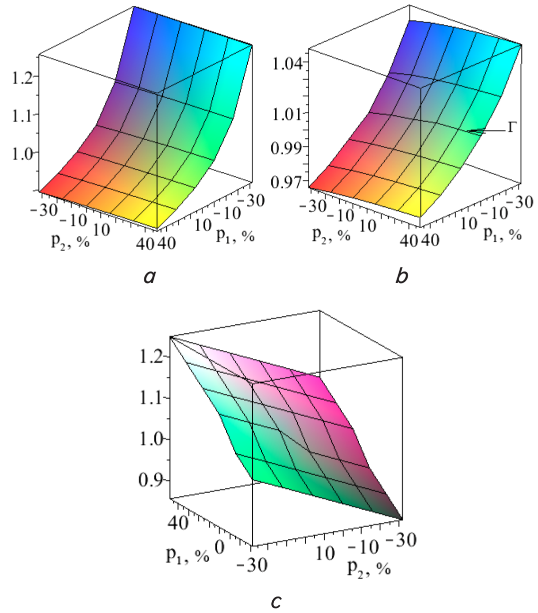


Fig. 11. Response surfaces for the variation in parameters of the force structure of a semi-wagon: *a* – relative displacements; *b* – relative stresses; *c* – relative mass

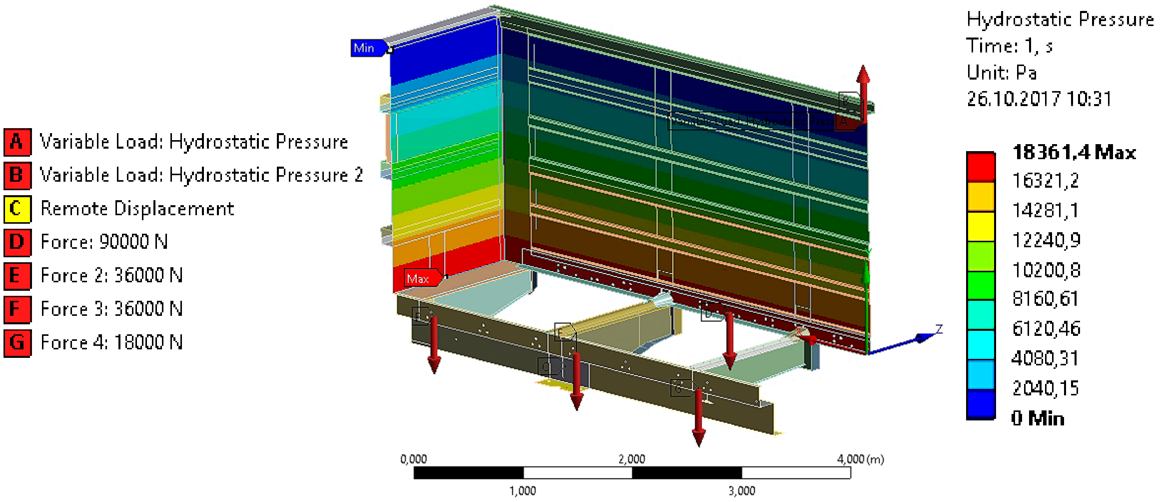


Fig. 10. Load application diagram

Here are the levels of function

$$m^{\hat{}}(p_1, p_2) = m(p_1, p_2)/m(p_1^0, p_2^0),$$

that characterizes a change in the mass of a semi-wagon due to the variation in parameters p_1, p_2. The dependences presented show that the influence of group of parameters p_1 in the vicinity of base values of parameters (p_1^0, p_2^0) is significantly larger than that of p_2. Accordingly, a variation in p_1 produces a greater win for stresses and deformations. In this case, the mass of a wagon changes insignificantly. Based on this, we substantiated design solutions for the examined structure.

Problem No. 4. Substantiation of design-technological solutions when designing a frame of the tractor cab.

We consider statement of the problem on optimization of a frame of the tractor cab to ensure a driver's safety zone in case of an accident, regulated by GOST 12.2.002.2-91. Impact on the cab is carried out from the front by a hard displacement of the specified plot of the frame at a certain distance Δ, Fig. 12. The assigned kinematic boundary conditions include fixation to prevent all displacements and turns in the region of the estimated model that corresponds to the place of installation of the frame on a tractor. The problem is solved in a physical and geometrical nonlinear statement.

It is assumed that the structural elements of the cab that are to the greatest extent responsible for the preservation of zone of a living space at a given load type are the crossbar of the roof, which directly receives load, and the cab racks. Thus, their thickness was varied – parameters p_1 and p_2, respectively. The obtained response surfaces of maximum stresses and reactive forces are shown in Fig. 13, *a, b*.

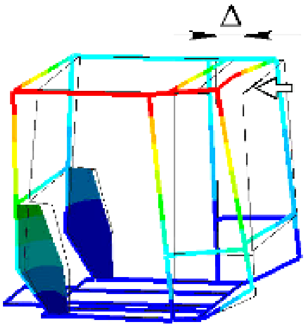
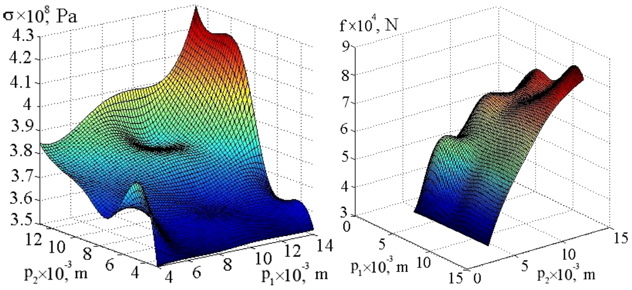


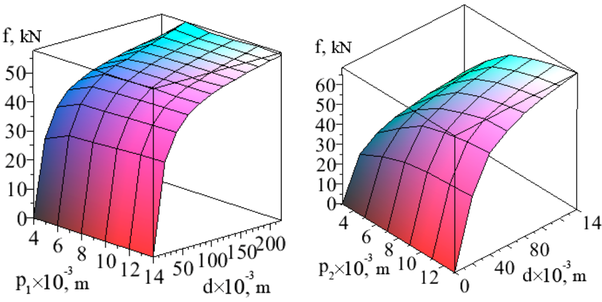
Fig. 12. Tractor cab loading



a *b*

Fig. 13. Response surfaces for the variation in parameters p_1 and p_2: *a* — maximum stresses; *b* — reactions in a support

Similar to problem No. 1, we also investigated dependences of the emerging reaction in the support at kinematic loading with an alternate change in parameters p_1 and p_2, Fig. 14, *a, b*, which became the basis for compiling recommendations for structural solutions to the frame of a tractor cab [6].



a *b*

Fig. 14. Dependence of the reaction that emerges in a support on the plate displacements when changing parameters: *a* — variation in parameter p_1; *b* — variation in parameter p_2

Problem No. 5. Synthesis of structural parameters of the body of the multipurpose tractor MT-L.

MT-L is a floating tractor, Fig. 15. One of the requirements put forward to its design is to maintain integrity and perform its functions when immersed in water with retention of buoyancy. Thus, in order for the newly designed or modernized body to meet this requirement, modeling of tractor motion when in water should be included in the list of estimated modes. The developed loading scheme includes the action of hydrostatic pressure on the body shell with a height of its application corresponding to the level of tractor's immersion into water due to its own weight, the weight of main aggregates and transported cargo. The constraints are assigned in such a way that they reflect a point in time when the MT-L caterpillars start to break away from the bottom. This is achieved by the introduction of elastic elements with low rigidity in the places of suspension fastening.

The task was to determine dependence of displacements, equivalent stresses by Mises, and the mass of the structure on the thickness of its structural elements. Parameter p_1 controls thickness of the sheets covering the bottom. It varied within 2–6 mm with a step of 1. Parameter p_2 is responsible for the value of thickness of the walls of cross-channel bars at the bottom of the tractor frame; it changed in the range of 2–10 mm with a step of 2, Fig. 15.

Fig. 16, *a–c* shows corresponding response surfaces of maximum magnitudes of displacements and stresses, as well as body mass for the variation in parameters p_1, p_2 under the action of applied external loads.

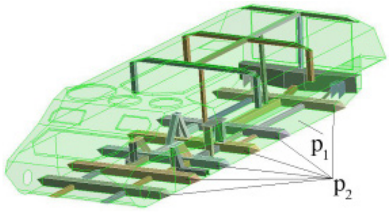
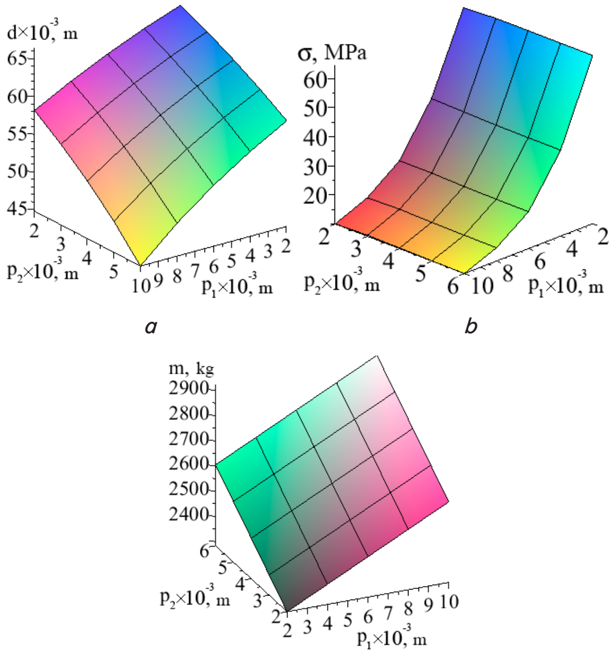


Fig. 15. Varied parameters of MT-L body

One can see that deflections of the bottom sharply increase at a decrease in its thickness. Even more dramatic are the equivalent stresses both at the controlled point of the bottom and, especially, maximal on the body. In combination with the linear dependence of mass of the MT-L body on the variation in parameters, we obtain information for making design decisions to substantiate the varied parameters [6]. What is important is that a given approach can be extended to a wide class of similar structures.



a *b*

c

Fig. 16. Response surfaces: *a* — maximal displacements; *b* — stresses; *c* — mass

Examples considered above do not cover the full diversity of tasks being solved and the design objects. At the same time, we have confirmed the applicability and effectiveness of the proposed approaches to solving applied problems for innovative thin-walled machine building structures.

6. Discussion of results of research into application of parametric approach to solving applied problems

Based on the parametric approach, we have set and devised complete statement of the problem on substantiation of design-technological solutions for innovative thin-walled machine building structures. The search for the solution to this problem involves 2 stages. At the first stage, based on heuristic approaches, we define basic structural and technological solutions for innovative products. Next, we substantiate separate parameters for the criteria ensuring strength and other characteristics. A distinctive feature of the models employed in this case is their variability, that is, adaptation to a change in the varied parameters, loads, criteria, and constraints. This property, on the one hand, sets them apart from those used under traditional statements of optimization problems, and on the other hand, it is extremely important in actual practice of development of innovative products. Thus, there is a natural connection between the required and provided properties that ensures fundamentally new possibilities for solving applied problems compared to conventional approaches.

In the course of present research we found dependences of strength characteristics of several thin-walled machine building structures on their design- technological parameters and operating modes. It was demonstrated that these dependences are multimodal in nature. In the case when in line with the proposed approach the objective function would also take into consideration a number of additional factors, then the resulting response surfaces could demonstrate a complex behavior pattern. In many cases, they are characterized by flatness and the presence of a large number of local extrema that are not clearly pronounced. In addition, there can occur ravines with a bottom along a complex trajectory. There are also breaks and jumps at the response surface. This peculiarity of the objective function presents a difficulty at optimization.

The proposed method of response surface approximation and search for optimal solution implies a combination of two processes – refinement of the discretization grid and shifting a discretization zone into the region of location of the current approximation to the solution. Thus, we have a kind of technology of a “grey box”, which implies, in contrast to variants of “white (transparent) box” and “black box”, obtaining a partial knowledge about behavior of the approximated function. Specifically, we proposed a linearization of change in the dependent parameters in the vicinity of the current point of parametric space. In this case, sensitivity of the controlled magnitudes for the variation in parameters is determined based on the finite-difference computations employing “reference” solutions to the problems of analysis. Position of the reference point, as well as magnitudes of parameter steps, determine the accuracy of approximation of the actual response surface, that is, the degree of “transparency” of the “gray box” improves. This property makes it possible to distract from the local features in behavior of the response surface, increasingly targeting global trends of its dependence on varied parameters. The fact is that a global optimum, being in the region of strong curvature of the response function is an area of high sensitivity of the examined characteristics for the variation in variable parameters. Thus, even a slight change, in the course of production, of the parameter values assigned for a project, as well as a change in the operational load, can exert a significant impact (typically, negative) on the strength and rigidity properties of the designed product. This shortcoming is absent in the proposed approach. At the same time, it should be noted that its application could lead to a loss (miss) of the more rational technical solution. However, this drawback is levelled off by repeatedly solving the problem solving with other initial points.

7. Conclusions

1. Based on parametric modeling, we developed an approach to providing design strength of innovative TWMBS. In this case, we improved the approach to approximation of the response function based on the combination of advantages of technology of a “black box” and a “transparent box”. In contrast to them, it is proposed to increase the degree of discretization of the search regions in the course of iterative process for refining the current approximation of the solution while shifting the region of discretization refinement toward a given current approximation.

2. In order to calculate sensitivity of several magnitudes for the variation in parameters, it is suggested using finite-difference ratios, and the priority is to construct an approximated response surface that reflects in general “global” trends of change in the solution, rather than “local”, as is the

case in traditional approaches. This makes it possible to find such a technical solution that, while not strictly optimal, is, however, first, close to it; second, it does not lead to a sharp deterioration in technical characteristics of innovative products when changing initial data.

3. By using a number of objects as examples, we found dependences of the controlled characteristics (stresses, mass, elastic displacements, etc.) on the varied parameters (for example, dimensions in a plan, cross-section and for thickness of TWMBS elements). Targeted variation of parameters enables determining their rational combination and, accordingly, recommendations for design and technological solutions. As a result, new technical solutions for innovative products are substantiated. Specifically, based on the present research, the recommendations are compiled for the substantiation of design parameters of innovative products: bus body frames that withstand the specified level of test loads; universal platform-wagons and railway semi-wagons with increased carrying capacity; force elements of the tractor cab for the criteria of providing a safety zone for the driver in case of overturning; force internal structure and shell of the multi-purpose tractor of MT-L family at modernization with maintaining buoyancy and strength.

In the subsequent research we expect to apply the proposed developments in order to substantiate technical solutions for a wide multitude of innovative thin-walled machine building structures.

References

1. Mathematical Modeling and Optimization of Complex Structures / Neittaanm ki P., Repin S., Tuovinen T. (Eds.). Switzerland: Springer, 2016. 328 p. doi: 10.1007/978-3-319-23564-6
2. Zarchi M., Attaran B. Performance improvement of an active vibration absorber subsystem for an aircraft model using a bees algorithm based on multi-objective intelligent optimization // Engineering Optimization. 2017. Vol. 49, Issue 11. P. 1905–1921. doi: 10.1080/0305215x.2017.1278757
3. Serpik I. N., Mironenko I. V., Averchenkov V. I. Algorithm for Evolutionary Optimization of Reinforced Concrete Frames Subject to Nonlinear Material Deformation // Procedia Engineering. 2016. Vol. 150. P. 1311–1316. doi: 10.1016/j.proeng.2016.07.304
4. Kuczek T. Application of manufacturing constraints to structural optimization of thin-walled structures // Engineering Optimization. 2015. Vol. 48, Issue 2. P. 351–360. doi: 10.1080/0305215x.2015.1017350
5. Innovatsionnyy vagon-tsisterna dlya perevozki legkovesnyh himicheskih produktov modeli 15-6899 / Chepurnoy A. D., Sheychenko R. I., Graborov R. V., Tkachuk N. A., Bondarenko M. A. // Podvizhnoy sostav XXI veka: idei, trebovaniya, proekty: materialy XII Mezhdnarodnoy nauchno-tekhnicheskoy konferentsii. Sankt-Peterburg: FGBOU VO PGUPS, 2017. P. 32–33.
6. Analysis and synthesis of complex spatial thin-walled structures / Marchenko A., Chepurnoy A., Senko V., Makeev S., Litvinenko O., Sheychenko R. et. al. // Proceedings of the Institute of Vehicles. Institute of Vehicles of Warsaw University of Technology. 2017. Issue 1. P. 17–29.
7. Nocedal J., Wright S. Numerical Optimization. 2nd ed. New York: Springer-Verlag, 2006. 664 p.
8. Chinneck J. W. Practical optimization: a gentle introduction. URL: http://www.sce.carleton.ca/faculty/chinneck/po.html
9. Zienkiewicz O. C., Taylor R. L., Zhu J. Z. The Finite Element Method: Its Basis and Fundamentals. 7th ed. Oxford: Butterworth-Heinemann, 2013. 756 p.
10. Sachsenberg B., Schittkowski K. A combined SQP–IPM algorithm for solving large-scale nonlinear optimization problems // Optimization Letters. 2015. Vol. 9, Issue 7. P. 1271–1282. doi: 10.1007/s11590-015-0863-x
11. Sample size selection in optimization methods for machine learning / Byrd R. H., Chin G. M., Nocedal J., Wu Y. // Mathematical Programming. 2012. Vol. 134, Issue 1. P. 127–155. doi: 10.1007/s10107-012-0572-5
12. Dinamicheskie i prochnostnye harakteristiki tonkostennyh elementov mashinostroitel'nyh konstruktsiy pri umen'shenii tolshchiny v protsesse ekspluatatsii / Tanchenko A. Yu., Tkachuk N. A., Artemov I. V., Litvinenko A. V. // Aktual'nye voprosy mashinovedeniya. 2013. Issue 2. P. 210–213.
13. Karmanov V. G. Matematicheskoe programmirovanie. 6-e izd. Moscow: Fizmatlit, 2008. 263 p.
14. Vasidzu, K. Variatsionnye metody v teorii uprugosti i plastichnosti. Moscow: Mir, 1987. 542 p.