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P.S. Shvets, PhD,
O.Yu. Lebedeva, Master,
V.V. Bondarenko, Master
Odessa National Polytechnic University, 1 Shevchenko Ave., 65044 Odessa, Ukraine; e-mail: pshvets@mail.ru

THE COMPUTER-AIDED DESIGN OF RUBBER-METAL PRODUCTS

П.С. Швець, *О.Ю. Лебедєва*, *В.В. Бондаренко.* **Автоматизоване проектування резинометалевих виробів.** У проектуванні сучасних резинометалевих виробів важливою проблемою є оптимізація їх маси при збереженні показників деформації в межах допустимих норм. ***Мета:*** Метою роботи є підвищення якості систем автоматизованого проектування через розробку і впровадження вдосконаленого методу оптимізації у САПР-К резинометалевих виробів, заснованого на «зворотній» оптимізації. ***Матеріали і методи:*** Розглянуто питання автоматизованого проектування конструкцій технічних композиційних виробів, які складаються з суттєво різних за властивостями анізотропних матеріалів. ***Результати:*** Запропоновано структуру САПР-К для розв'язання завдання такого проектування, і описано принципи роботи її підсистем. Показано, що оптимізація у САПР повинна враховувати як обмеження об'єктивно існуючий зв'язок оптимізуючих аргументів між окремими елементами цих систем у визначеній області. ***Висновки:*** Розглянуто проблему «зворотної» оптимізації, коли цільовими функціями є параметри області зв'язності, що в багатьох випадках дозволяє отримати ефективніші рішення в процесі автоматизованого проектування. Розроблена САПР-К була задіяна при виробництві гумовометалевих амортизаторів на Одеському заводі гумових виробів з позитивним техніко-економічним ефектом.

Ключові слова: параметри зв'язності, «обернена» оптимізація, САПР конструкцій, композиційні вироби.

P.S. Shvets, *O.Yu. Lebedeva*, *V.V. Bondarenko.* **The computer-aided design of rubber-metal products.** The important problem in design of rubber-metal products is the optimization of their mass without sacrificing of proportionality factor is in the limits of standard. ***Aim:*** The aim of this work is to improve the computer-aided systems by development and implementation of improved optimization method in rubber-metal CAD systems for designers based on the reverse optimization. ***Materials and Methods:*** The paper studies the matters of computer-aided structural design of technical composite products composed of anisotropic materials that are essentially different in properties. ***Results:*** The structure of CAD systems for designers solving the problems of such design is offered and the work principles of its subsystems are described. It is shown that complicated systems optimization in CAD systems must consider as restrictions the entitative connection between separate elements of these systems within the area of the optimizing arguments. ***Conclusions:*** The problem of the "reverse" optimization when objective functions are the connectivity area parameters is considered. In many cases, this allows receiving solutions that are more effective during the computer-aided design process. The developed CAD system for designers was used during the production of rubber-metal shock absorbers at the Odessa Rubber Technical Articles Plant. The positive technical and economic effect was obtained.

Keywords: connectivity parameters, "reverse" optimization, constructions CAD system, composite products.

Introduction. In various industries, such as shipbuilding, mechanical engineering etc., to absorb vibrations and shock waves the multilayer shock absorbent systems are used. They consist of elastic and inelastic layers able to dampen vibrations and withstand heavy loads under the effect of an external perturbation. These systems need an appropriate adapted comprehensive approach to the formulation and solution of optimization problems. This allows taking into account not only the different material properties of elements, but connections between elements. Thus, the improvement of existing methods of multilayer systems calculation and optimization taking into account the different material properties of elements and connections between them is an actual problem.

For effective solution of many optimization problems of complex systems in CAD is important the result of the appropriate objective function selection. With such choice the attention should be paid not only to the functional parameters of the designed system, but also to some of the initial constraints given from the outside, which are so important for the characteristics of future systems that it would be better to receive it as a result of optimization. Obvious examples of such constraints may serve the several standard sizes of machines and mechanisms, limit rotation speed and rectilinear motion of certain parts and units in mechanics, "the passport" voltages and currents in electrical equipment etc. However, the less obvious parameters of the systems exist, that are "secondary" in optimization

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problems solving and some that occur only because of deep analysis of the processes that take place in designed object during its lifecycle. The coupling factors of complicated systems elements can be referred to such parameters, in the possibility of virtual or real influence on this complexity and to find at the expense of this influence the additional opportunities to create modern products with "over-optimal" properties. In view of ever-increasing demands on quality of the products, technologies and modern production equipment, it can be argued that searching and development of such optimization methods is extremely important.

The most common shock absorbent systems today can be referred to rubber-metal products of various purpose [1…3] and related to composite materials [4, 5]. Physically, the products of this type represent the anisotropic environment, where the distribution of mechanical interactions depends on the direction and application of external forces [6]. Optimization of such systems in CAD is a difficult task, because it is necessary to take into account substantially different material properties of system components. Unfortunately, current methods allow calculation of the elastic elements of the system only, despite the fact that real-life systems are significantly more complex.

Based on this fact, such products CAD systems for designers are formulate and solve the problems of design optimization of rubber-metal products, that provide, for example, better conditions of shock-waves attenuation [7].

As it known, an optimization is the searching of arguments vector $\mathbf{x}$, providing the extremum of some objective function $f(\mathbf{x})$ [8]. A multicriteria optimization is a process of simultaneous optimization of two or more conflicting objective function in within the definition range [9].

The multicriteria optimization problem consists in solution vector searching (set of optimizing arguments), that comply with imposed restrictions and optimizes some common vector function which elements corresponded to specific objective functions (1). The last-named are forming the mathematical description of satisfiability criteria and, as a rule, mutually collide. Therefore, to optimize is to find such solution, by which the values of specific objective functions it would be acceptable according to given problem [10].

It is often occurs a problem with computer-aided design of systems, induced by specific parameters of one or another system appertains to two or more its elements at the same time [11]. For example, when designing a reduction unit it is impossible to optimize the gear rotation speed without accounting of another gear situated at the same shaft with the first one [12]; it is impossible to design the switch-off schedule of one part of the electronic device without compounding of design results with another part if they have common switcher [13] and so on.

Similar connections between parameters of elements are the hard restriction to system totally. For example, on sequential elements design the designed are the parameters of only first of it, and for subsequent ones they are automatically put in set of initial data.

Such approach may both simplify the design process (at least one design parameter less) and essentially complicate it (this forcing repeatedly return to already designed elements or to design the system entirely at one time. In this case, the comprehensive genetic algorithm is used to solve the optimization problem. New constraints satisfaction unit [14] supplements this algorithm.

Recently papers show that the aforementioned connections between elements of the systems are not rigid [15]. The existence of such connections allows solving optimization problems of systems more effectively than by Pareto [16]. In this case, the using of complex genetic algorithms complemented by adaptation units of calculation models for "flexible" connection between arguments of objective functions of multicriteria optimization [17].

That does not take account of entirely new mathematical possibilities of "reverse" optimization, i.e. finding the optimal design solution, when aforementioned restrictions caused by nonrigid connections are "transferred" into the set objective functions, because the parameters of these connections depend on object design parameters and its producing technology.

The aim of this work is to improve the quality of computer-aided design systems by development and implementation of improved optimization method in rubber-metal CAD systems for designers based on the "reverse" optimization.

Materials and Methods. In the process of construction design the multicriteria optimization used for such parameters of construction, that provide defined strain distribution in composite systems, momentum transfer, distribution of sound wave between the elements of composition or dependency of noisiness on their properties and so on.

As it mentioned earlier, to solve the problem of multicriteria optimization with multidimensional closely coupled arguments in CAD systems are used evolutional methods and algorithms, i.e. complex genetic algorithm (CGA) assigned for permanent solution monitoring in the evolution process to avoid the connectivity constraints disturbance. Moreover, in CAD systems are applied the ramified complex symbol models of the design object genotype, containing elements parameters connected in different way [18, 19].

Let consider the possibility of "overoptimal" solutions obtaining, i.e. performing of virtual multicriteria extended optimization by Pareto – more effective than by Pareto [20]. It is possible, when arguments are weakly connected (can take values different for every objective function. These values may be of own existence domain $x_{\min} \le x \le x_{\max}$; $x \in \mathbf{x}$, but only such values, that in addition appertain to the certain "coherence range" ($x^c_{\max} \ldots x^c_{\min}$). In turn, this range appertains to the certain multi-dimensional coherence domain **b,** which entirely lays in existence range and it is less than mentioned one. As a result, there have been obtained one optimization problem and two solutions for it in the general case: x^* and x^{**}, which obtain the inequality $f_{1\text{opt}}(x^*) \ne f_{2\text{opt}}(x^{**})$.

The extended Pareto optimum is situated under the upper-bound and above lower-bound estimates for two optimization extremes — independent and closely coupled.

As it known, the general problem of multicriteria optimization is formulated in this way [8]:

$$\min_{\mathbf{x}}\{f_1(\mathbf{x}), f_2(\mathbf{x}), \cdots, f_k(\mathbf{x})\}, \quad \mathbf{x} \in Q, \tag{1}$$

where f_i: $R^n \to R$ ($i = \overline{1,k}$, $k \ge 2$) — objective functions,

$\mathbf{x} = (x_1, x_2, \ldots, x_n)$,

Q — domain of a function.

Let write the common expression (1) as a direct two-criteria problem of two-arguments function optimization, where its components coincide partially:

$$\min_{\mathbf{x}_1,\,\mathbf{x}_2}\{f_1(\mathbf{x}_1, \mathbf{x}_2), f_2(\mathbf{x}_1, \mathbf{x}_2)\}, \quad \mathbf{x}_1 \in Q_1, \mathbf{x}_2 \in Q_2 \tag{2}$$

where $f_1(\mathbf{x}_1, \mathbf{x}_2)$, $f_2(\mathbf{x}_1, \mathbf{x}_2)$ — objective functions,

$\mathbf{x}_1$, $\mathbf{x}_2$ — optimizing vector,

Q_1, Q_2 — domain of corresponding objective functions.

If there is loosely correlation between optimizing vectors then such expression can be written:

$$\mathbf{x}_1 = \mathbf{x}_2 + \mathbf{b}, \tag{3}$$

where **b** — vector size of connectivity domain. It should be pointed out, that dimensionality of this domain is equal to quantity of connected components of optimizing vectors. If after analysis process of specific design item it turns out that dimensionality of connectivity domain is equal to zero, then the optimization process ca be performed separately: $f_1(\mathbf{x}_1, \mathbf{x}_2)$ on $\mathbf{x}_1$ and $f_2(\mathbf{x}_1, \mathbf{x}_2)$ on $\mathbf{x}_2$.

The value **b** of connectivity domain during the direct optimization problems solving occurs in restrictions sets and assigned by analysis of future object. If connectivity domain is of stochastic nature then the probability of deviations $\mathbf{x}_1$ and $\mathbf{x}_2$ in the domain range depends on object properties and its operation conditions. During the optimal design process, the connectivity domain can be shifted and change the size **b**, which is also a random value. However, the parameters of loosely coupled elements will always remain inside the connectivity domain. Within the reverse optimization problem solution, as objective functions are chosen not the object properties but the size of connectivity domain **b**:

$$\min_{\mathbf{x}_1,\,\mathbf{x}_2}\{\mathbf{b}\}, \quad \mathbf{x}_1 \in Q_1, \mathbf{x}_2 \in Q_2\,. \tag{4}$$

As stated above, this provides additional possibilities of CAD systems, because the parameters of the objective functions $f_1(\mathbf{x}_1, \mathbf{x}_2)$ and $f_2(\mathbf{x}_1, \mathbf{x}_2)$ reflect some properties of the design object, and the parameters of connectivity domain **b** usually reflect absolutely other properties — which are left without attention during “standard” optimization.

Such approach allowed to create “RUMET-D” CAD system for designers (*rubber metal designing*), intended to computer-aided design of any variety and materials composition rubber-metal products, that are part of compositions (fig. 1). First of all, they include: rubber-containing power unit, for example, shock absorbers; metal products with rubber protective covering, for example, caterpillar tracks, submarine body surfaces; metal-armored rubber, for example, automobile tires; metal-filled rubber, for example, sealers for hermetic cameras, and more[21].

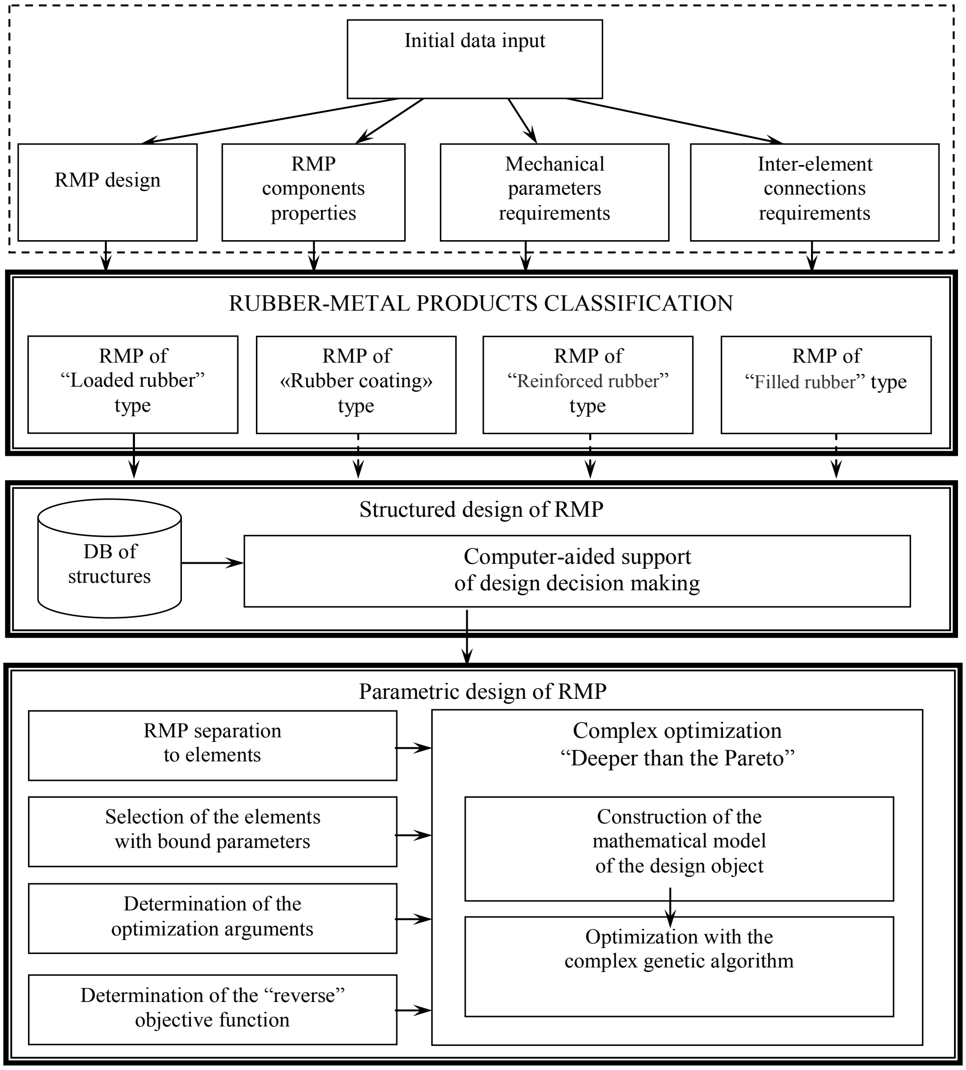


Fig. 1. The structure and main subsystems of the “RUMET-D” CAD system for designers

For every type of rubber-metal product are inherent its own problems during the design process. The power unit must have preplanned durability; the rubber coating must have necessary cohesion with metal base and preplanned mechanical characteristics, which are rubber compound depending; metal-armoring rubber parameters depend on armoring construction, and properties of loaded rubber depend on design of corresponding equipment.

The "RUMET-D" CAD system for designers consists of rubber-metal products classification units by types, structure design unit and parametric design unit, that has ability to find connections between properties of system elements and use them during optimization process of this elements.

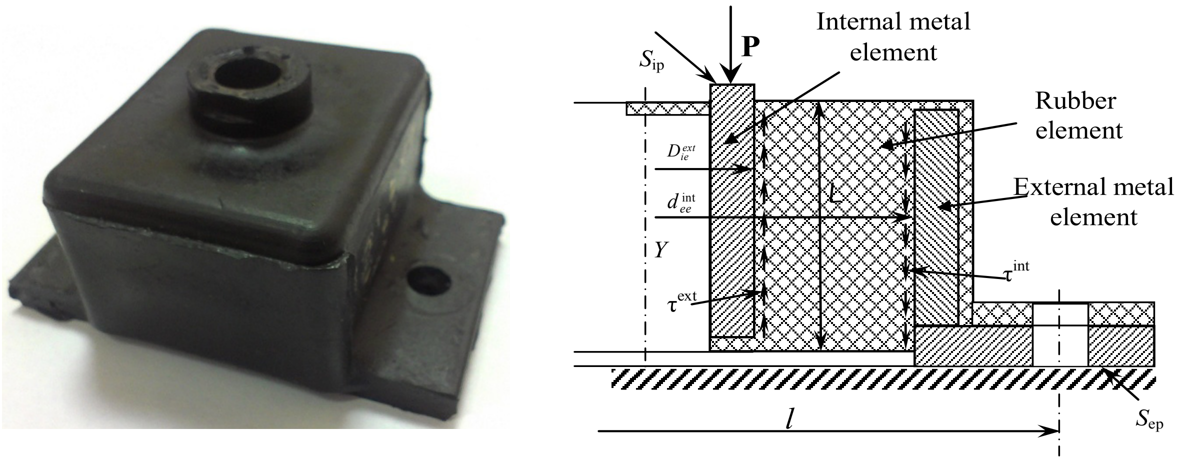
Let review the solving of optimization problem using "RUMET-D" CAD system for designers with simple example of shock absorbers for mechanical rubber AKCC (shock absorber welded ship with insurance) (Fig. 2, *a*).

The AKCC shock absorbers are designed to work in air environment with oil and diesel vapors, as well as with probable direct ingress of oil, diesel fuel, fresh and sea water; at temperatures from –5 till +70 ºC, and short-term (no longer than 1 hour and no more than once a month) at temperatures from –10 till +100 ºC, and out-of-action at temperature of –40 ºC during the completion and holding of ships [22].

The shock absorbers are designed to work in vibratory mode with frequency up to 50 Hz with amplitudes of rubber array warping in the line of X, Y and Z axes up to 0,2 mm.

The technical specification for design is formulated in a certain way: to design a rubber-metal block absorber of "Loaded rubber" type, structurally designed in the form of three concentric pipes: metal – rubber – metal (Fig. 2, *b*), where amortize forcing P in line of Y axe is applied on the internal metallic pipe and on over the rubber and external metallic pipe is transmitted to support.

The aim of the optimization is to minimize the shock absorber mass M on retention of specified conditions.



a *b*

Fig. 2. The common view (a) and analytical design (b) of rubber-metal shock absorber AKCC-10 M

Optimizing arguments: D_{ie}^{ext} — external diameter of internal metallic element; d_{ee}^{int} — internal diameter of external metallic element; L — heights of internal and external metallic and rubber elements; S_{ip} — square of internal support point; S_{ep} — square of external support point.

Restrictions: [τ] — threshold limit value of tangential stress at the boundary of metal — rubber; [σ] — threshold limit value of internal stresses in rubber.

Results. It is known, that rubber-metal product as a system at least consists of two subsystems – metallic and rubber, which are in physical synergy (mutual environment, interpenetration, adhesion contact). Let pick out tree subsystems in AKCC shock absorber: internal metallic element, rubber element and external metallic element (Fig. 2, *b*). Let determine the design parameters (optimizing arguments), which connect these elements by rigid and nonrigid connections (table 1).

Table 1

The АКСС shock absorber elements and their interconnections, considered during the optimization process

System	Rubber-metal product: АКСС shock absorber		
Subsystems	Internal metallic element	Rubber element	External metallic element
Uncoupled Arguments	S_{ip} — size of internal support point	—	S_{ep} — size of external support point
Loosely Coupled Arguments	D_{ie}^{ext} — external diameter of internal metallic element	—	d_{ee}^{int} — internal diameter of external metallic element
Tightly Coupled Arguments	L — height of internal metallic element	L — height of rubber element	L — height of external metallic element

As it can be seen, even in the simplest rubber-metal shock absorber there are arguments, related to all listed sets of subsystem elements and distinguished by coupling form.

The optimization objective function will looks in the following way:

$$M = M_{ie} + M_{re} + M_{ee} + M_{se}, \quad (5)$$

where M_{ie} — the mass of internal metallic element;

M_{re} — the mass of rubber element;

M_{ee} — the mass of external metallic element;

M_{se} — the mass of secondary elements, for example, support points.

If to let all parameters (within the equation (5) but not mentioned in design task) as constants, it is possible to write objective function in the general form:

$$M = f(D_{ie}^{ext}; d_{ee}^{int}; L), \quad (6)$$

then the multicriteria (three-criteria) optimizing problem (1) will be in the following way:

$$\min_{M}\left\{M_{ie}(D_{ie}^{ext}; d_{ee}^{int}; L), M_{re}(D_{ie}^{ext}; d_{ee}^{int}; L), M_{ee}(D_{ie}^{ext}; d_{ee}^{int}; L)\right\},\ D_{ie}^{ext}; d_{ee}^{int}; L \in Q. \quad (7)$$

Considering the proposed optimization method, let deduce tightly coupled and uncoupled arguments from (7) to constants. As result the expression were obtained:

$$\min_{M}\{M_{ie}(D_{ie}^{ext}; d_{ee}^{int}), M_{re}(D_{ie}^{ext}; d_{ee}^{int}), M_{ee}(D_{ie}^{ext}; d_{ee}^{int})\},\ D_{ie}^{ext}; d_{ee}^{int} \in Q. \quad (8)$$

Any optimization method for problem (8) must consider nonrigid connection of form (3) between D_{ie}^{ext} and d_{ee}^{int}:

$$d_{ee}^{int} - D_{ie}^{ext} \le [b]. \quad (9)$$

It follows from loading diagram (fig. 2b), that [*b*] — maximum permissible wall thickness of rubber cylinder, determined by maximum permissible deformation (compression) of shock absorber on load. At the same time, [*b*] limits the distance between nonrigid connected parameters D_{ie}^{ext} and d_{ee}^{int}.

We have to emphasize, that the question is *not about tolerance of rubber element size, but about connectivity domain of metallic elements optimizing parameters.* The connectivity domain, as it mentioned earlier, determines the possibility of deeper design optimization of whole shock absorber.

Let review the balance conditions in line of Y-axis to build the mathematical model of coherence. This model are built for the static load of shock absorber according to scheme on Fig. 2, b. For the external metallic element, this condition looks in this way:

$$\tau^{ext} \pi D_{ie}^{ext} L = P, \quad (10)$$

and for internal one:

$$\tau^{int}\pi d_{ee}^{int}L = P\,. \tag{11}$$

As the τ^{ext} for such loading scheme is always larger than τ^{int}, so the strength condition looks like:

$$\tau^{ext} = \frac{P}{\pi D_{ie}^{ext}L} \le [\tau]\,. \tag{12}$$

Plugging in the expression (12) the equation for coherence (9) was obtained:

$$\frac{P}{\pi(d_{ee}^{int} - [b])L} \le [\tau]\,, \tag{13}$$

that is the computed model for multicriteria functions M_{ie}, M_{re} and M_{ee} optimization by arguments D_{ie}^{ext} and d_{ee}^{int} and restrictions on [*b*] and [τ].

Let solve the expression (13) with respect to [*b*]:

$$[b] \ge d_{ee}^{int} - \frac{P}{\pi L[\tau]}, \tag{14}$$

that is the computed model for function [*b*] optimization by the same arguments, but with the restrictions on d_{ee}^{int} and [τ].

Solving the tasks (8), (9) and (14) together, we will find such [τ] and d_{ee}^{int}, providing minimal [*b*] value, at that, the [τ] value directly connected with the rubber compound and its vulcanization technology. In addition, the d_{ee}^{int} value connected with shock absorber design, which offers to designer wide possibilities on optimal design of this production limits.

If add to the initial design problem except tangent stresses between the metal and rubber the normal ones (as in real shock absorber), we obtain, in terms of computational models, statically indeterminate system, which have the set of characteristic features [23]. In particular, to calculate statically indeterminate systems it is necessary to specify before the geometric characteristics of cross sections of the elements, i.e. their actual shapes and sizes, because the changing of these characteristics leads to changing of forcing in connections and new forces distribution in every element of the system. In addition, it is necessary in advance to choose material of construction during calculation of statically indeterminate systems, because it is necessary to know its elasticity modulus.

It is slightly complicate the calculations during the optimization process on [*b*], because specified characteristics are already chosen as restrictions.

Conclusion. It is established, that approach to design rubber-metal products constructions as design of systems consisting of subsystems with coupled parameters allows improving quality indexes of such systems through “overoptimal” optimization of their design characteristics.

As follows from the analysis of problems and methods of computer-aided design for connected technical objects, using CAD system were performed setting and proposed improved method to solve the optimization problems for loosely coupled technical systems. It was performed due to use as an objective function the optimization of the connectivity domain size of the objective function arguments. This offers additional capabilities for designer, because the parameters of the objective functions reflect some design object properties, and parameters of connectivity domain, generally, reflect another ones, which are left without attention during “standard” optimization.

It was theoretically proven and practically confirmed (using computer experiment and production testing) the opportunities to increase the speed of design and product quality of rubber-metal products using CAD systems, providing effective parameter optimization of loosely coupled subsystems of the design object with the objective function in the form of connectivity domain. It was proposed for this the “RUMET-D” CAD system for designers as a part of common “RUMET” CAD system. The main function of this system is the design of rubber-metal products constructions. The testing of “RUMET-

D” CAD system for rubber-metal products design based on proposed method for obtaining “over-optimal” technical solutions at the JSC “Odessa Rubber Technical Articles Plant” were performed.

The construction of rubber-metal shock absorber АКСС-10М was used as a computer-aided design object. The test results with maximum static load showed that shock absorber, designed using “RUMET-D” CAD system, resulted 5,6 % mass loss without sacrificing of proportionality factor in the limits of standard.

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