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THE VIRTUAL MODELS IN EQUAL-STRESSED MACHINE PARTS DESIGN

A. Stanovskyi, Y. Naumenko, I. Saukh, O. Abu Shena
The Odessa national Polytechnic University
prosp. Shevchenko, 1, Odessa, 65044, Ukraine. E-mail: ostanovskyi@gmail.com

Purpose. The purpose of this study is reduction of metal machinery parts while maintaining their operational reliability by further development of the virtual models method by increasing efficiency optimizing configuration and dimensions of the symmetrical components under acting loads. **Methodology.** The main characteristic configurations of many machine parts is their symmetry. Accounting for the symmetric properties of the design creates new opportunities to simplify the work with the standard programs using the finite element method. **Results.** Modifications to the pipe equal cross-section fitting under the external loads with purpose of mechanical stress uniform distribution in tube equal resistance allows to reduce metal consumption of the structure without significant loss of its reliability. The problem of optimal in the above sense of design is reduced to the calculation of such design details, which, after load preset forces would ensure uniform distribution of mechanical stresses throughout volume, in the case of the above example, as the length of the pipe and on any of its cross section. It is shown how this problem is solved for a wide range of tasks using the method of the virtual model. Examples of solving such problems for statically determinate systems. **Originality.** For the first time conducted a comprehensive study of the mechanical stress condition of the machine parts, which allowed to propose a new design method of the latter with the use of intermediate models. **Practical value.** A method is proposed in which the model of the future design object transformation, some intermediate States which can exist only in the virtual view. This way it helps find such intermediate state, in which the optimization of geometric characteristics can be performed most efficiently. The method involved when you design a symmetrical bottoms of tanks of variable thickness, working under pressure, with positive technical and economic effect. References 11, tables 0, figures 5.

Key words: machine parts, equal-stressed, virtual models.

ВІРТУАЛЬНІ МОДЕЛІ В ПРОЕКТУВАННІ РІВНОНАПРУЖЕНИХ ДЕТАЛЕЙ МАШИН

О. Л. Становський, Є. О. Науменко, І. А. Саух, О. Абу Шена
Одеський національний політехнічний університет
просп. Шевченко, 1, м. Одеса, 65044, Україна. E-mail: ostanovskyi@gmail.com

Головною характеристикою конфігурації багатьох машинобудівних деталей є їхня симетрія. Врахування симетричних властивостей конструкції створює нові можливості для спрощення роботи зі стандартними програмами, що використовують метод скінченних елементів. Метою цього дослідження є зниження металоємності деталей машин при збереженні їх експлуатаційної надійності шляхом подальшого розвитку методу віртуальної моделі за рахунок підвищення ефективності оптимізації конфігурації і розмірів симетричних деталей в умовах діючих навантажень. Запропоновано метод, в якому модель майбутнього об’єкта проектування піддається перетворенню, деякі проміжні стани якого можуть існувати виключно у віртуальному уявленні. Такий шлях допомагає знайти такий проміжний стан, в якому оптимізація геометричних характеристик може бути виконана найбільш ефективно. Метод задіяний при проектуванні симетричних днищ резервуарів змінної товщини, які працюють під тиском, із позитивним технічним та економічним ефектом.

Ключові слова: деталі машин, рівнонапружений, віртуальна модель.

PROBLEM STATEMENT. The main configurations characteristic of many machine parts is their symmetry. Accounting for the symmetric properties of the design new opportunities to simplify the work with the standard programs using the finite element method (FEM) where creates [1].

The only limit to these possibilities is the need to preserve the symmetry under transformations of the structure related to its optimization. If such optimization concerns the geometric properties of a part, then this step is very difficult, as the optimal design under asymmetric loading, as a rule, are not symmetrical.

Cross-section elements of the supporting structures traditionally chosen depending on the available range of rolled products or are made, usually close to symmetric shapes: round, ring, square, rectangle, hexagon, etc.

Such section, despite its adaptability, often don’t provide uniform distribution of stress loads. The problem is how to develop a design method that allows to find new non-symmetrical cross section, providing, however, equal stress in detail [2, 3].

Work goal. The purpose of this study is the reduction of metal machinery parts while maintaining their operational reliability by further development of the method of the virtual models by increasing efficiency optimizing configuration and dimensions of the symmetrical components under acting loads.

To achieve this objective in the work were solved following tasks:

– improved method of virtual models of equal to the stress machine parts;

– showing the virtual model method application to the solve a one-dimensional design tasks of the equal to a busy rod configuration suspended by one end;

– solved the task of designing statically indeterminate rod, clamped on both ends;

– completed a practical test of the method in the calculation of the tank bottom with a positive technical effect.

EXPERIMENTAL PART AND RESULTS OBTAINED. Consider a simple example [4, 5]. When loading a round tube according to the scheme shown in Fig. 1 *a* stress distribution along the pipe axis have the form shown in Fig. 1 *b*. Modifications to the pipe equal cross-section fitting under the external loads with the purpose of mechanical stress uniform distribution in the tube equal resistance allows to reduce metal consumption of the structure without significant loss of its reliability.

A similar phenomenon is observed when considering the reconciliation of an equivalent stresses plot in the cross section of the circular pipe (Fig. 2).

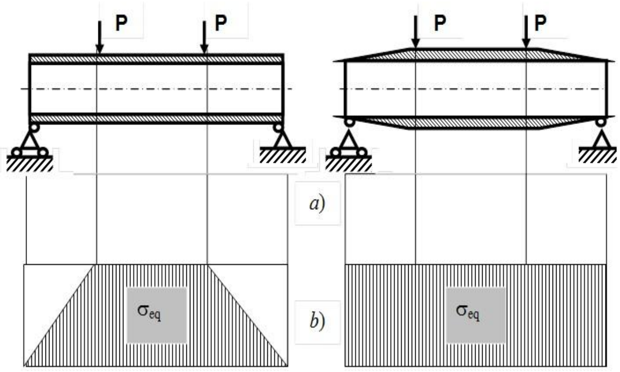

Figure 1 – Scheme of equal pipes loading longitudinal section (left) and equal stress (right)

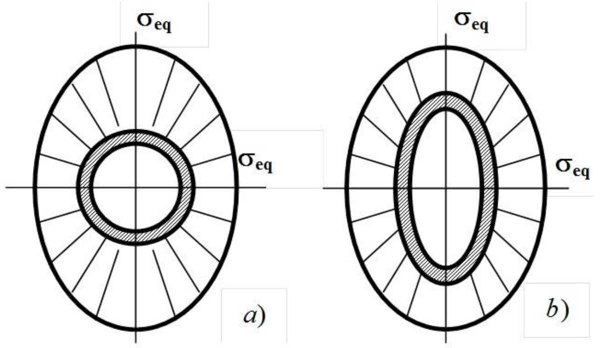

Figure 2 – The transition from a pipe of equal cross-section (left) to the tube equal to the voltage (right)

And here the change in cross section of the pipe for the purpose of uniform stress distribution to optimize the design, turning it into a pipe of equal stress.

The problem of optimization in the above sense of design is reduced to the calculation of such design details, which, after load preset forces would ensure uniform distribution of mechanical stresses throughout the volume, in the case of the above example, as the length of the pipe and on any of its cross section.

This calculation by analytical methods is challenging, even when using modern computers. The solution to the problem by the finite element method is complicated by the fact that the cross section is equal to the resistance opposed to the round can't be beat for a large number of symmetric elements.

If you are breaking some design into finite elements and the scheme and parameters of external loading, the stress-strain state (SSS) of each finite element is determined by the settings of the stiffness of the material from which it is made, its shape and dimensions, as well as external (concentrated or distributed) load.

If these specific parameters are equal for the two finite elements, and their SSS is also equivalent (Fig. 3).

As can be seen from the figure, in the three-factor case, the compensation of the error in one factor can be made due to the misalignment of the second or third factors individually or their combined action [7].

Application of the method for the calculation of statically indeterminate systems [8]. As mentioned above, the dependence of the distribution voltage from element stiffness design exists only in statically indeterminate systems.

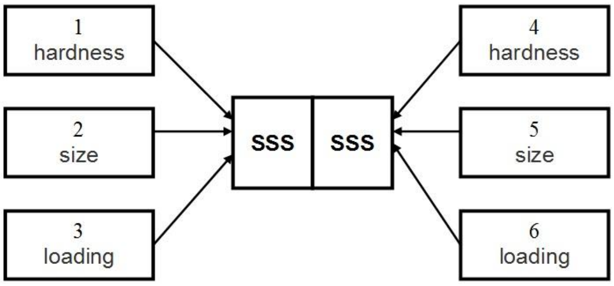

Figure 3 – The scheme of two piece design SSS formation

When the inequality parameters of at least one the factors is natural to assume the equivalence of the SSS (Fig. 4 *a*). This equivalence can be theoretically eliminated by the violation of the other factor equality (Fig. 4 *b*), which acts on SSS in the «opposite» direction [6].

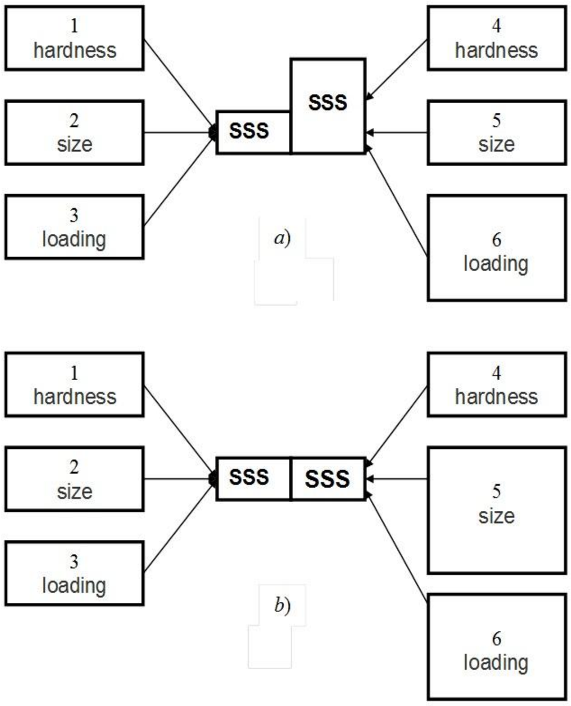

Figure 4 – The scheme to the role of factors influencing SSS assessment

Consider the example of solving such problem in one-dimensional statement. Let the round vertical rod, clamped the upper end of the loaded weight and the current along its axis the power *P*. If the length *L* and the material of the rod is given, the uneven distribution of stresses and deformations it can be compensated by the virtual uniformity of the cross-sectional area *F*, the hardness *E* or the external load *P*.

Accordingly, there are three types of virtual rods: size compensating stiffness compensating and external loading compensating (and possible combinations of these types).

The virtual object with an compensate for the size. Divide the rod into *n* sections of equal length *l* and «allow» these sections have the different (but constant within a phase) diameter D_i ($i = 1, ..., n$).

Will find the ratio of these diameters so that the stress plot in the rod was close to uniform. It will be closer to uniform than in more parts of the broken rod. Thus, the problem can be solved with any prescribed accuracy.

The virtual object with compensating rigidity. We introduce a methodological complication in the problem. Let, by analogy with the sensitivity to the asymmetry of finite elements CAD, the existing algorithm finite elements method (FEM) does not allow to simulate the rod elements of different diameter. As in statically determinate systems, stress does not depend on the material stiffness of the rod, will speak about the alignment of stresses and deformations. Use in this case, the circuit shown in Fig. 4, and will try to compensate for the uneven distribution of the strains are the dimensions of the part and its stiffness. That is, replace rod of equal strength and hardness, but of different diameters, a rod of equal strength and diameter but of unequal hardness.

The result is a virtual terminal, consisting of different stiffness sections. Almost a pin (in a strictly defined properties of real substances limits) can be made of different materials, but we are interested in a virtual object, the value of E_i in areas which can take any value.

Thus, having satisfied the requirement of the newly introduced restrictions, that is, keeping intact the diameter of the rod elements, using the FEM package, sensitive to the variability of elements sizes to adjust the values of $E_1, ..., E_i, ..., E_n$, provides approximately (with any predefined accuracy) equal strain along the length of the rod. Note that this, the most time consuming part of the calculations performed by the computer and the designer. Now remained outside of the package, using the ratio $D_i = f(E_i)$, derived for σ = const, using the known values E_i to determine values of D_i for each element of the core, restoring the equality of the stiffness for all elements. The project real web optimal design is ready.

Virtual object with a compensating external loading. We fix the average value of equivalent stress $\overline{\sigma}_{eq\ i}$ in *i*-th element when the estimated loading force *P* and the acceleration of gravity *g*. We then mentally change the loading, selecting such values $P_1, …, P_{i-1}, P_{i+1}, …, P_n$ and $g_1, …, g_{i-1}, g_{i+1}, …, g_n$, which provide close to the stress $\overline{\sigma}_{eq\ i}$ value of all the other elements. The load in turn applied to all the elements simultaneously, but each loading provides a predetermined value $\overline{\sigma}_{eq\ i}$ only their element; the other elements at the time of the application «alien» load stress will differ from $\overline{\sigma}_{eq\ i}$ that in the framework of this method does not matter.

Thus, the dimensions of the rod the same way as in the previous case, remain at this stage unchanged, which gives the possibility to use for the selection of the loadings are sensitive to the dimensional parameter software package.

The result is a series of virtual external forces $P_1, …, P_{i-1}, P, P_{i+1}, …, P_n$ and the virtual acceleration of gravity $g_1, …, g_{i-1}, g, g_{i+1}, …, g_n$, which is already outside of the package can be converted into a number of rod diameters equal tension, reducing the singular values of the external force and the acceleration of gravity, i.e., making the rod very real.

Therefore, the example of applying the method of virtual objects [9] to the use of an object with virtual stiffness consider the example of loading of a rod, whose scheme is shown in Fig. 5.

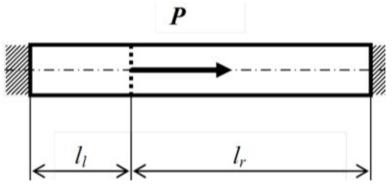

Figure 5 – An example of a statically indeterminate loading horizontal rod

Horizontal rod, rigidly clamped at the ends, loaded the current along its axis by a force *P* applied at a distance l_l from its left edge and l_r – in from the right and the dividing plane for your application the rod into two parts – left and right.

The effect of gravity is neglected. It is known that in this case there are three functions: σ_l, σ_r, $\Delta\sigma$ two variables: F_l, F_r, which specified relationships:

$$\sigma_l = P\frac{l_r E_l}{l_l E_r F_r + l_r E_l F_l}; \tag{1}$$

$$\sigma_r = P\frac{l_l E_r}{l_l E_r F_r + l_r E_l F_l}; \tag{2}$$

$$\Delta\sigma = \sigma_l - \sigma_r = P\frac{l_r E_l - l_l E_r}{l_l E_r F_r + l_r E_l F}, \tag{3}$$

where σ_l, σ_r – accordingly, the stress in the left and right parts of the rod; F_l, F_r – section of the left and right sides; E_l, E_r – the stiffness of the rod parts.

Analysis of equations (1) – (3) shows that, unfortunately, the condition $\Delta\sigma = 0$ is impossible at finite F_l, F_r. This corresponds to the statement that in statically indeterminate structures in the general case all elements at the same time it is impossible to obtain equal stress.

Therefore speech can go only about minimizing $\Delta\sigma$, and the whole problem reduces to the optimization with three optimization criteria – σ_l, σ_r, $\Delta\sigma$, two variables – F_l, F_r and restrictions.

Its formulation for our example is follows.

To find the optimal values F_l^* *and* F_r^*, *where* $|\Delta\sigma| \to \min$, $\sigma_л \to \max$, $\sigma_п \to \max$ *and are the following limitations:*

$$\sigma_l \le [\sigma]; \tag{4}$$

$$\sigma_r \le [\sigma]; \tag{5}$$

$$F_{l\,\min} \le F_l \le F_{l\,\max}; \tag{6}$$

$$F_{r\,\min} \le F_r \le F_{r\,\max}. \tag{7}$$

The solution of the optimization problem with three optimization criteria presents significant challenges and does not provide a clear end result. Therefore, as the only optimization criterion chosen was the total mass m of the design part (host).

In our example, the total mass of the rod *m* or, equivalently, its metal content can be determined according to the formula:

$$m = m_l + m_r = \rho\left(l_l F_l + l_r F_r\right), \tag{8}$$

and its optimal (lowest) value respectively equal to:

$$m^* = \rho\left(l_l F_l^* + l_r F_r^*\right). \tag{9}$$

Let us analyze the expression (9). As mentioned above, the value Δσ = 0 is unattainable. The geometric meaning of the constraints (4) and (5) is that they are cut from the rectangle of the argument region in which the condition of strength.

For each pair of arguments in (8) can be calculated from the value of the mass of the rod. A pair of values $F_л^*$ and $F_п^*$, which providing the minimum value of the mass m^*, will solve the problem, that is the space of sections of parts of the rod the least mass that meets the requirements of (4) to (7).

Problem was solved by numerical method, for which the field of argument was covered with mesh, the nodes which were calculated pairs of values F_l, F_r. For each node was calculated values of stresses in both parts of the rod. If these values are not exceeded, the received for this node the value of m compared with m-values in other nodes and choosing the minimum.

In the transition to a virtual method of the rigidity value of the cross-sectional area of the whole stem were recorded at baseline, and the sorting in the grid nodes were subjected to values of moduli of elasticity is now different in the left and right sides.

In this algorithm, minimization subjected to the absolute value of the difference between stresses in various parts of the rod:

$$\Delta E = \left|E_l - E_r\right|. \tag{10}$$

The objective of the calculation is to find the minimum cross – section, wherein the selection of the E_l and E_r still manages to ensure implementation of the inequalities (4) and (5).

Here is a concrete example of applying the method of virtual stiffness to calculate the optimal core designs loaded according to the scheme (Fig. 5).

Initial data for calculation: the length of the left part of the rod – l_l = 0,4 m; the length of the right part of the rod – l_r = 0,6 m; the external force – P = 10000 N; allowable stress is – 120 MPa; the nominal value of the elastic modulus of real material rod – E_{nom} = 200000 MPa; the density of the material of the rod – ρ = 7800 kg/m^3.

Step 0. Believe σ_l = [σ] and by the formula (1) defined the value of F_l, that provides the left part tension equal to [σ]:

$$F_l = \frac{P}{[\sigma]}\cdot\frac{l_l}{l_l + l_r} = 0{,}5\cdot 10^{-4}\ \text{m}^2\,. \tag{11}$$

As in step 0 the rod has a uniform cross-sectional area $F_r = F_l = F_0^*$, the tension in the right side:

$$\sigma_r = \frac{P}{F_r}\cdot\frac{l_l}{l_l + l_r} = 80\ \text{MPa}\,. \tag{12}$$

Thus, all of the rods of equal cross section has the smallest mass m_0^*:

$$m_0^* = \rho\cdot F_0^*(l_l + l_r) = 0{,}39\ \text{kg}\,. \tag{13}$$

Step 1. From design considerations to select the boundaries of variation: $F_{l\ \min}$ = 0,000035 m^2; $F_{l\ \max}$ = 0,0002 m^2; $F_{r\ \min}$ = 0,000035 m^2; $F_{\text{r max}}$ = 0,0002 m^2.

Define square sections F_{l1}^* and F_{r1}^*, that providing m_1^*:

$$\begin{gathered} F_{l1}^* = 0{,}60\cdot 10^{-4}\text{m}^2; \\ F_{r1}^* = 0{,}36\cdot 10^{-4}\text{m}^2; \\ m_1^* = 0{,}3559\ \text{kg} \end{gathered} \tag{14}$$

at stresses equal to 119,0476 MPa in left and 79,36507 MPa in right parts.

Calculated the relative change in the cross-sectional area in the transition from step 0 to step 1:

$$\Delta F_l = \frac{F_{l1}^*}{F_0^*} = 1{,}54\,; \tag{15}$$

$$\Delta F_r = \frac{F_{r1}^*}{F_0^*} = 0{,}22\,. \tag{16}$$

Step 2. Select the border of the variation of the stiffness: $E_{l\ \min}$ = 100 000 MPa; $E_{l\ \max}$ = 250 000 MPa; $E_{r\ \min}$ = 100 000 MPa; $E_{r\ \max}$ = 250 000 MPa.

Virtual determined values of moduli of elasticity E_{l2}^* and E_{r2}^*, that providing m_2^*:

$$\begin{gathered} E_{l2}^* = 1{,}66\cdot 10^{11}\text{MPa}; \\ E_{r2}^* = 2{,}49\cdot 10^{11}\text{MPa}; \\ m_2^* = 0{,}3276\ \text{k}g\,. \end{gathered} \tag{17}$$

Calculated the elastic modulus relative change in the transition from step 1 to step 2:

$$\Delta E_l = \frac{E_{l2}^*}{E_{\text{nom}}} = 0{,}83; \tag{18}$$

$$\Delta E_r = \frac{E_{r2}^*}{E_{\text{nom}}} = 1{,}245 \cdot \tag{19}$$

Step 3. Count the rod area by the method of virtual models, based on the ratios:

$$\frac{F_{l3}^*}{F_0^*} = \frac{E_{\text{nom}}}{E_{l2}^*}; \tag{20}$$

$$\frac{F_{r3}^*}{F_0^*} = \frac{E_{\text{nom}}}{E_{r2}^*}. \tag{21}$$

Using (20) and (21), obtain:

$$F_{l3}^* = \frac{F_0^* \cdot E_{\text{nom}}}{E_{l2}^*} = 0{,}602 \cdot 10^{-4}\,\text{m}^2; \tag{22}$$

$$F_{r3}^* = \frac{F_0^* \cdot E_{\text{nom}}}{E_{r2}^*} = 0{,}4 \cdot 10^{-4}\,\text{m}^2, \tag{23}$$

what provides the stress in the left part 115,119 MPa and right – 76,746 MPa at weight m_3^* = 0,375 kg, that is within the normal range. Comparing F_{l1}^* and F_{r1}^*, then F_{r1}^* and F_{r3}^*, then m_1^* and m_3^*, we find that these values are exceedingly close.

Especially it should be noted that the final result (22) and (23) were obtained without using the data of step 1, only where the rod is composed of two parts of unequal cross sections.

For design stages using does not recognize the asymmetry of CAD, detail of the left symmetrical in form, allowing other factors – properties and the external loading to make very exotic (virtual) values.

And only at the last stage, these factors acquire the features of reality through shape recovery [10]. Thus the «whimsical» CAD manages to fool on the information level and result-set to design asymmetric, complex shapes, and thus optimal, parts and components.

A method is proposed in which the model of the future design object transformation, some intermediate States which can exist only in the virtual view. This way it helps to find such intermediate state, in which the optimization of geometric characteristics can be performed most efficiently. The method involved when you design a symmetrical variable thickness bottoms of tanks [11], working under pressure, with positive technical and economic effect.

CONCLUSIONS. Under asymmetric mechanical loading (that is most often found in machine) is optimal asymmetric design details, the design of which, as a rule, very hardly. Modern computer software means for calculation of stress-strain state of parts and components sharply increase its effectiveness only when given the symmetry of the structure. In this case a real significant gain in conflict with the requirement of optimality of the latter, – «symmetric» CAD can't design asymmetrical shape of the part.

There is a vicious circle: then detail farther from the symmetry, so it is «better», but the harder in modeling and design.

Method of virtual object allows to overcome these contradictions. For this for design stages using does not recognize the asymmetry of CAD, detail of the left symmetrical in form, allowing other factors – properties and the external loading to make very exotic (virtual) values. And only at the last stage, these factors acquire the features of reality through shape recovery. Thus the «whimsical» CAD manages to fool on the information level and result-set to design asymmetric, complex shapes, and thus optimal, parts and components.

A method in which the model of the future design object transformation, some intermediate states which can exist only in the virtual view is proposed. This way it helps to find such intermediate state, in which the optimization of geometric characteristics can be performed most efficiently. The method involved when you design a symmetrical variable thickness bottoms of tanks, working under pressure, with positive technical and economic effect.

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REFERENCES

1. Goncharova, O. E., Maksimov, V. G. (1999). Nechuvstvitelnyiy k asimmetrii chislennyiy metod optimizatsii konstruktsiy. *Trudy Odesskogo politehnicheskogo universiteta, Vyip.* 2(8), pp. 41–44.

2. Reddy, J. N., Mousavi, S. M., Romanoff, J. (2016). Analysis of anisotropic gradient elastic shear deformable plates. *Acta Mechanica,* pp. 1–18.

3. Novikov, V. V., Maksimov, V. G., Balan, S. A., Goncharova, O. E. (1999). Matematicheskoe modelirovanie profilya ravnogo soprotivleniya. *Optimizatsiya v materialovedenii, Odessa: AstroPrint*, 151 p.

4. Balan, S. A., Goncharova, O. E., Maksimov, V. G. (1999). Optimizatsiya profilya balok osey mobilnyih mashin pri proektirovanii. Vestnik Hersonskogo gosudarstvennogo tehnicheskogo universiteta, Spets. Vyip., *Prikladnyie problemyi matematicheskogo modelirovaniya, Herson, Veta-Poliprint*, pp. 32–33.

5. Stanovskiy, A. L., Maksimov, V. G., Goncharova, O. E. (1998). Optimizatsiya profilya nesuschih elementov metallokonstruktsiy. *Naukoviy visnik OGPU, 6*, pp. 139–144.

6. Gaschuk, P. M., Zoriy, L.-M. (1999). Liniyni modeli diskretno-neperervnyh mehanichnyh system. LvIv: *Ukrayinski tehnologiyi*, 372 p.

7. Aryassov, G., Gornostajev, D. (2013). The calculation of round plates under the action of local loading by generalized functions. 13th International Symposium «*Topical Problems in the Field of Electrical and Power Engineering*», pp. 296–299.

8. Hu, W., Feng, N. S., Hahn, E. J. (2004). A comparison of techniques for identifying the configuration

state of statically indeterminate rotor bearing systems. *Tribology international. University of New South Wales, Sydney, NSW 2052, Australia, 37, 2*, pp. 149–157.

9. Maksimov, V. G., Goncharova, O. E., Stanovskaya, T. P. (1999). Raschyot parametrov NDS metallokonstruktsiy metodom virtualnogo ob'ekta. *Modelirovanie v prikladnyih nauchnyih issledovaniyah, Odessa: OGPU*, pp. 16–17.

10. Daschenko, O., Stanovskyi, O., Khomiak, Yu., Naumenko, E. (2016). Mathematical model of connections cylindrical shell with the bottom variable thickness. *«Information technology and automation – 2016»: Proceedings IX Annual scientific conference, Odessa, ONAFT*, pp. 29–30.

11. Zamihovskiy, L. M., Pankiv, H. V. (2007). Otsinka napruzheno-deformovanogo stanu vertikalnyh stalnyh tsilIndrychnyh rezervuariv za peremischennyami tochok yih poverhni. Nauchnyiy zhurnal «*Vestnik Kremenchugskogo natsionalnogo universiteta imeni Mihaila Ostrogradskogo», 4(45), 1*, pp. 141–144.

ВИРТУАЛЬНЫЕ МОДЕЛИ В ПРОЕКТИРОВАНИИ РАВНОНАГРУЖЕННЫХ ДЕТАЛЕЙ МАШИН

А. Л. Становский, Е.А. Науменко, И. Саух, А. Абу Шена

Одесский национальный политехнический университет

просп. Шевченка, 1, г. Одесса, 65044, Украина. E-mail: ostanovskyi@gmail.com

Главной характеристикой конфигурации многих машиностроительных деталей является их симметрия. Учет симметричных свойств конструкции создает новые возможности для упрощения работы со стандартными программами, использующих метод конечных элементов. Целью настоящего исследования является снижение металлоемкости деталей машин при сохранении их эксплуатационной надежности путем дальнейшего развития метода виртуальной модели за счет повышения эффективности оптимизации конфигурации и размеров симметричных деталей в условиях действующих нагрузок. Предложен метод, в котором модель будущего объекта проектирования подвергается преобразованию, некоторые промежуточные состояния которого могут существовать исключительно в виртуальном представлении. Такой путь помогает найти такое промежуточное состояние, в котором оптимизация геометрических характеристик может быть выполнена наиболее эффективно. Метод задействован при проектировании симметричных днищ резервуаров переменной толщины, работающих под давлением, с положительным техническим и экономическим эффектом.

Ключевые слова: детали машин, равнонагруженный, виртуальная модель.

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