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TO THE ISSUE OF SOLVING THE INVERSE TASKS OF MULTI-CRITERIA IDENTIFICATION OF VOLUME HYDRAULIC MACHINES

У роботі обґрунтовано ефективність методу дослідження простору параметрів для рішення зворотних задач багатокритеріальної ідентифікації на прикладі шестерінчастого насоса зовнішнього зачеплення з прозорим корпусом, розробленого у «Вроцлавській політехніці». Покращена математична модель об'єкта дослідження шляхом введення рівнянь радіального і нормального бокового зазорів, що підвищило її адекватність і дозволило визначити три вихідних даних, відсутніх у технічній документації. Знайдені значення коефіцієнта висоти ніжки зуба, бічного і радіального зазорів спільно з іншими відомими вихідними даними дозволяють побудувати 3D комп'ютерну модель для подальшого дослідження в програмі обчислювальної гідродинаміки робочого процесу насоса.

Ключові слова: ідентифікація, математична модель, пряма і зворотна задачі ідентифікації, багатокритеріальні задачі ідентифікації, критерії адекватності.

В работе обоснована эффективность метода исследования пространства параметров для решения обратных задач многокритериальной идентификации на примере шестеренного насоса внешнего зацепления с прозрачным корпусом, разработанного в «Вроцлавской политехнике». Улучшена математическая модель объекта исследования путем ввода уравнений радиального и нормального бокового зазоров, что повысило ее адекватность и позволило определить три исходных данных, отсутствующих в технической документации. Найденные значения коэффициента высоты ножки зуба, бокового и радиального зазоров совместно с другими известными исходными данными позволяют построить 3D компьютерную модель для дальнейшего исследования в программе вычислительной гидродинамики рабочего процесса насоса.

Ключевые слова: идентификация, математическая модель, прямая и обратная задачи идентификации, многокритериальные задачи идентификации, критерии адекватности.

The work proves the effectiveness of the parameter space investigation method for solving inverse tasks of multi-criteria identification by the example of an external gear pump with a transparent casing developed at the Wroclaw Polytechnica. The mathematical model of the object of investigation was improved by introducing the equations of radial clearance and normal backlash, which increased its adequacy and allowed to determine three input data that are absent in the technical documentation. The found values of the dedendum coefficient, backlash and radial clearance together with other known input data allow to build the 3D computer model for further investigation of pump working processes in the CFD program.

Key words: identification, mathematical model, direct and inverse identification tasks, multi-criteria identification tasks, adequacy criteria.

Introduction

The issue of the conformity (adequacy) of mathematical models (MM) to real objects is an important scientific and experimental problem. This is achieved by formulating and solving identification tasks. A large range of methods and algorithms for identification has been accumulated. It is shown that the classification of identification tasks can be carried out for a number of features. The article proposes a multi-criteria identification, the effectiveness of which is confirmed by solving the tasks for mechanical systems. In general, let's call such identification problems as direct tasks.

In science and practice, there is also a reverse situation, when the manufactured sample doesn't have a number of parameters required for development and study of computer models. Here, these parameters should be found by using the improved MM. We call such identification problems as inverse tasks.

This article is devoted to the formulation and solution of inverse identification tasks by the example of an external gear pump (GP).

Analysis of literary sources

In work [1], the authors note that parametric identification (direct identification tasks) in the modern theory of automatic control is the ability to determine the MM parameters of system or process according to results of measuring the certain output values of a real system for a certain time interval. The authors of work [1] state that although the term "identification" was applied in the 60th years of the XX century, identification in a broad sense is an integral part of science (of many scientific areas).

In practice, a multi-criteria approach to identification tasks was effective in the example of mechanical systems based on the method of studying the parameter space or the data parameters investigation method [2, 3]. In the general case, when studying the complex systems, it cannot be asserted that the MM corresponds to a real object. In this case it is difficult to manage with one indicator (criterion) of adequacy as in traditional direct identification tasks. In the multi-criterion formulation, it is possible to assess the adequacy of the model according to the set of local proximity criteria. The essence of the authors' approach to the direct task of multi-criteria identification includes the following: there are characteristics (criteria) $\Phi_v^c(\alpha), v=\overline{1,k}$ determined from the analysis of the MM describing the object under study, $\alpha=(\alpha_1,\ldots,\alpha_r)$ – vector of parameters of the model under study. There is Φ_v^{exp} – experimental value of the *v*-th criterion measured with sufficient accuracy directly on the prototype sample or on the prototype. The number of them should be sufficient for the correct statement of the identification task. Comparing the calculated $\Phi_v^c(\alpha), v=\overline{1,k}$ characteristic and experimental characteristic of the model, it is necessary to determine the conformity of the model to the real object and to find the parameter vectors α^i, which satisfy three types of limits:

parametric

$$\alpha_J^* \le \alpha_j \le \alpha_j^{**},\ j=\overline{1,r}; \quad (1a)$$

functional

$$c_l^* \le f_l(\alpha) \le c_l^{**},\ l = \overline{1,t}\ ; \qquad (1b)$$

criterial

$$\left\| \Phi_v^c(\alpha^i) - \Phi_v^{exp} \right\| \le \Phi_v^{**}. \qquad (1c)$$

These limits define the allowed set $D\alpha$ [2]. Here Φ_v^{**} – criterial limits, which are assigned in the process of the researcher's dialogue with the computer on the ground of the analysis of test tables. The determined vectors α^i belonging to the $D\alpha$ are called adequate. The algorithm includes the essence of multi-criteria (vector) parametric identification.

Formulation of the task

It follows from the above review that the solution of direct identification tasks in the field of the modern theory of automatic control is an actual direction, which is of practical and scientific interest. The nature of the tasks to be solved is associated with an increase in the adequacy of the model to the real object. The emergence of a reliable model on the basis of solving the identification tasks by using the data parameters investigation method has become a new trend in the theory and practice of identification. The nature of the identification tasks to be solved in this direction also relates to the adaptation of the model to the real object.

Let's consider the GP as an object of multi-criteria identification. When calculating and developing a gearing (G) of a pumping unit, we usually use the packages (programs) for calculating the mechanical transmissions, which have a mathematical model closed for the user and are oriented to designing the power mechanical transmissions in accordance with regulatory documents. As a result, the documentation (drawings) does not contain a number of parameters that are included in the equation of the gearing geometry of the hydraulic machine pumping unit. For example, the absence of parameters h_f^* (dedendum coefficient) and J_n (normal backlash) in the source data and technical (design) documentation indicates that the gears were calculated with using a mechanical transmission calculation package, where the input data do not require the setting of these parameters (for example, “*Compass*” of the Russian company “*ASCON*”). The absence of the value $X_{\min}$ in the input data may indicate the application of a gearing calculation program of Swiss company *KISSsoft*.

Let’s consider the formulation of the identification task when the inverse task of finding the unknown values h_f^* and J_n is solved with the help of MM that takes into account all features of the GP pumping unit gearing as a hydraulic machine.

The practice of GP gearing calculations, incl. calculations with the help of *Compass* program, shows that the calculation of a non-gaping engagement is most often performed, while the real clearance is provided by tolerances for manufacturing the gears and pump casing.

In this case, the program *KISSsoft* (Switzerland) can be used to calculate and build drawings of a gear pump. The program is oriented to mechanical transmissions, and its mathematical support is based on DIN standards [4-6]. The program uses the parameter h_f^* in the input data to calculate the gearing. As for gaps J_t, J_n and J_r, this problem is solved in the program on the basis of tolerances and corresponding equations (DIN [5, 6]). These three gaps can be seen in the resulting protocol of the *KISSsoft* program after calculating the gearing. From the analysis of the protocol data, it can be stated that these parameters are not included in other equations of the *KISSsoft* calculation model.

In work [7], one of the recommendations for mechanical transmissions is to calculate the non-gaping engagement, and in the documentation, the backlash is provided by tolerances for the manufacture of gears. However, back in 1957, in the first edition of monograph [8] by E. M. Yudin about the gear pump, the author proposed a formula that links two important parameters: coefficient of profile displacement X and center-to-center distance a_w by means of the gearing angle (α_w) with allowance for the backlash:

$$X = \frac{z \cdot (\mathrm{inv}\,\alpha_w - \mathrm{inv}\,\alpha) - \dfrac{J_n \cdot \cos\alpha_w}{2 \cdot m \cdot \cos\alpha}}{2 \cdot \mathrm{tg}\,\alpha}. \qquad (2)$$

The numerator of expression (2) includes a backlash. The author showed the influence of this parameter on the hydrodynamics of GP internal processes, on the flowing of working fluid (WF) from the chamber of higher pressure into the chamber of low pressure, on pulsation of instantaneous flow, etc. Thus, in the gearing MM, an equation was introduced to take into account the backlash.

The influence of the backlash on the parameters of the GP operation is evident from the work of American researchers from Youngstown State University [9], which is devoted to the two-dimensional numerical modeling of the internal hydrodynamics of a working fluid flow rate in the gear pump. The PGP gear pump (number of teeth - 11, working volume - 50 cm^3) of Parker Hannifin Corp make was used as the object of research. Fig. 1 shows the curves of mass flow rate as a function of time (of the gear rotation angle) at the pump outlet. The mass flow rate (Fig. 1), as a function of time, is a sinusoidal curve and does not change with time.

In general, according to the authors, the results confirm that the size of the backlash is the most significant parameter that affects the pump flow rate. In DIN standards and in *Compass* and *KISSsoft* computation programs, there is no dependence (2).

It should be noted that in *KISSsoft*, the parameter of radial clearance C is calculated in absolute values (DIN [6]).

In the domestic literature and in the *Compass* program, the coefficient C^* is included in the input data and its values are clearly regulated in order to standardize the cutting tool for making mechanical gears.

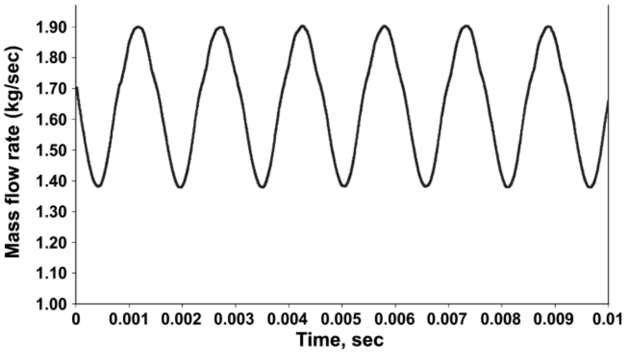

Fig. 1 – Mass flow rate curve in numerical modeling of a working fluid flow in the gear pump with the backlash of 30 μm, rotation frequency of 3000 rpm and pressure of 3000 psi (iteration step is $1{\cdot}10^{-6}$ s, the number of iterations is 10 000)

Let's note that when the formulas (3a), (3b) and (3c), which determine the actual center-to-center distance, are substituted into equations (DIN [6])

$$\alpha_w = \alpha \cdot \frac{\cos\alpha}{\cos\alpha_w}, \quad (3a)$$

tip diameter

$$d_a = 2a_w - d + 2m\left(h_a^* - x\right), \quad (3b)$$

and reference diameter

$$d = m \cdot z, \quad (3c)$$

we obtain the following expression:

$$C = \left(h_f^* - h_a^*\right) \cdot m. \quad (3d)$$

If we do not use numerical values for the coefficients h_a^* and $C^* = C/m$, and follow the basic rack profile of the tool (Fig. 2b, GOST 13755-68), then we obtain the formula (3e):

$$h_f^* = h_a^* + c^*. \quad (3e)$$

It follows from formula (3e), that only h_a^* and no any other value is one of the most important augends of the dedendum coefficient. As can be seen from Fig. 2 (theoretical basic rack profiles of the tool) this rigid requirement is not present: the dedendum size without a radial clearance can be not equal to the addendum size.

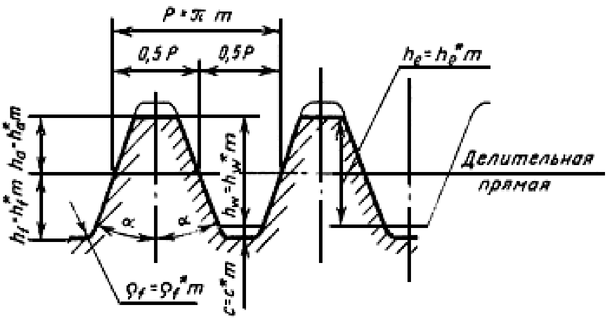

Fig. 2 – Theoretical basic rack profile of the tool (GOST 13755-81)

As follows from the analytical review, to determine two unknown parameters on the real gear pump, it is necessary, according to the general setting (1a) – (1c) of the multi-criteria (vector) parametric identification of the task, to construct a mathematical model, with the help of which a multi-criteria optimization task is solved within the framework of solid state mechanics under optimization criteria, and under the adequacy criteria, the identification task is solved. In our opinion, the basis of such a model for a gear pump can be the DIN equations [4 – 6], formula (2), backlash equations from work [7], working volume [8], etc.

Functional limits, the performance of which ensures the GP operability [7, 8], are represented by inequations that show the need to fulfill limits on geometric and kinematic parameters in the identification process for:
minimum displacement

$$X > X_{\min}; \quad (4)$$

gear teeth height

$$H \le 0{,}25m; \quad (5)$$

thickness of tooth tip on addendum circle

$$S_a \ge 0{,}2m; \quad (6)$$

minimum clearances of gears

$$C^* \ge 0{,}5/m; \quad (7)$$

and others.

Adequacy criteria

When choosing criteria for adequacy, the recommendations set forth in [2, 3] were used. In this case, we took into account the peculiarity of the inverse task, which consisted in comparing the correspondence between the selected known values of the object parameters and the calculated values obtained in the course of search for unknown parameter values of J_n and h_f^* of the object. In this case, the parameters of the model and the object are indicated by upper indices, with the letters "m" and "ob", respectively.

The following expressions are used as criteria for adequacy:

$$\Phi_1 = \left|d_a^{\mathrm{m}} - d_a^{\mathrm{ob}}\right|; \quad (8)$$

$$\Phi_2 = \left|d_f^{\mathrm{m}} - d_f^{\mathrm{ob}}\right|; \quad (9)$$

$$\Phi_3 = \left|V_0^{\mathrm{m}} - V_0^{\mathrm{ob}}\right|; \quad (10)$$

$$\Phi_4 = \left|X^{\mathrm{m}} - X^{\mathrm{ob}}\right|; \quad (11)$$

$$\Phi_5 = \left|h_a^{\mathrm{m}} - h_a^{\mathrm{ob}}\right|. \quad (12)$$

The original GP with a transparent casing (Fig. 3), created in the "Wroclaw Polytechnica" under the guidance of Professor Ja. Stryczek, was taken as an identification object. Works [10, 11] are devoted to experimental studies of this pump on the bench (Fig. 4), with the help of which it is possible to carry out not only the determination of characteristics, but also visualize the flow in the working part of the pump.

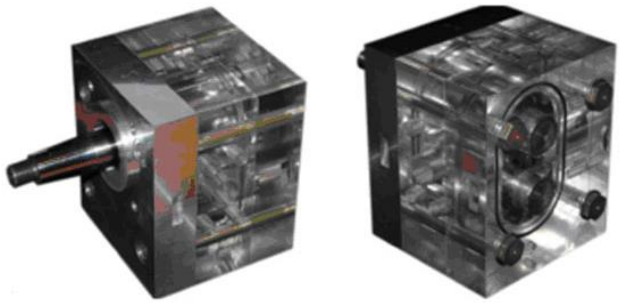

Fig. 3 – Design of the experimental pump

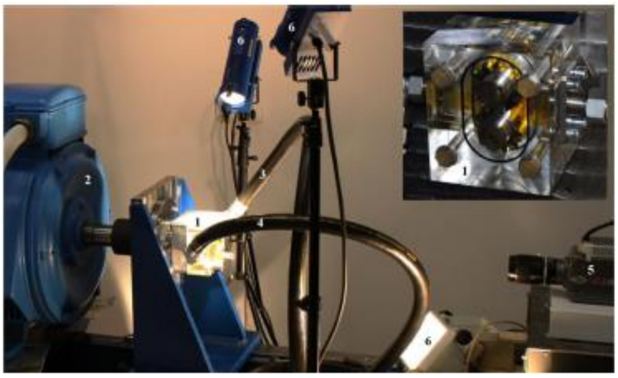

Fig. 4 – Photo of the test bench for the experimental pump

Experimental studies were carried out with a working fluid of HLP-68 grade with a kinematic viscosity of 68 mm^2/s at $T = 40^0\text{C}$. The curves of pressure pulsations on the suction and pressure lines were received, while video recording (10000 frames/s) fixed the moments of the appearance and collapse of cavitations bubbles. To build a computer model of this pump three input parameters were unknown: h_f^*, J_n and C^*.

Let us turn to their search. At the first stage, the following intervals of variable parameters were adopted. Generally, they make up the parametric limits: dedendum coefficient of basic rack $h_f^* = 1{,}15\ldots1{,}365$, normal backlash $J_n = 0{,}025\ldots0{,}045\,mm$ and addendum coefficient of basic rack $h_a^* = 1{,}15\ldots1{,}19$. In addition to the parametric limits, functional limits were introduced. In the course of solution, 495 trial variants of the gearing and the pumping unit, as a whole, were considered, from which 64 decisions have satisfied the given conditions and the specified restrictions accepted in the model. These decisions make up the set G (the parallelepiped Π subset consisting of points satisfying the parametric and functional limits). At this stage, a linear relationship between the accepted criteria was estimated by determining the correlation coefficients [3, 12]. In general, the correlation analysis allows us to more deeply assess the formulation of the identification task in terms of selecting: the assigned criteria and their number, intervals of parametric and criterial limits, the variable parameters, and, on the whole, it allows to clarify the formulation of the task.

At the second stage, the criterion limits were introduced into the model and the intervals of the variable parameters were changed as follows: $1{,}15 \le h_a^* \le 1{,}17$; $1{,}335 \le h_f^* \le 1{,}365$; $J_n = 0{,}03$. 495 test solutions make up a test table containing 35 solutions, which constitute an admissible set $D\alpha$. On the basis of a dialogue with the OPT software system of multi-criteria optimization [13], the results of various functions of processing the information of the test table can be displayed on the monitor screen by the command system. Table 1 gives the results of search of limit values for each criterion with an indication in which decision (at which point in the test table) they are listed.

The data of Table 1 show that the minimum values of all criteria are contained in points 5 and 23, including the criterion F4X equal at all points, including point 23. These two decisions should be considered as precedents for choosing the best solution. Table 2 shows the values of the criteria at points 5 and 23, on the basis of which it is possible to give preference to solution 5.

Table 1 – Limit values of criteria F1 to F5 in the test table with indication of the point number

Criterion No	***Fi*.max /Point *No***	***Fi*.min / Point *No***
*F*1*da*	0,065 mm / 21	0,051 mm / 5
*F*2*df*	0,275 mm / 19	-0,02 mm / 23
*F*3*Vo*	0,115 cm^3 / 21	-0,02 cm^3 / 23
*F*4*X*	-0,007 / 1-35	-0,007 / 1-35
*F*5*ha**	-0,001 / 21	-0,002 / 5

In addition, the values of the required parameters of the inverse problem being solved are given for points 5 and 23 in Table 2. After rounding the values of variable parameters h_a^* and h_f^* and p.5 to the third decimal place and after performing the local identification, the search for the best solution of the inverse multi-criteria identification task is completed (Table 3).

Table 4 shows the values of the geometric and kinematic parameters for the gearing of the best solution.

To calculate geometrical parameters of the gearing according to input data (highlighted in Table 4) is of practical importance in any program, for example, in the KISSsoft program, in order to evaluate the proximity of the proposed mathematical model for solving the inverse identification task as well as of the *KISSsoft* program model (Table 5, 6 are constructed according to the protocol).

Table 5 shows the values of the adequacy criteria, which were calculated from equations (8 – 12), where the values of the parameters with the index "M" were taken from the protocol of the *KISSsoft* program.

Parameters that have a small difference are shown in the tables in a dark color. In general, the comparison of the data of Tables 4, 6 and 3, 5 shows sufficient practical accuracy of geometrical parameters of the gearing and the accuracy of adequacy criteria obtained on the basis of the model under discussion by means of *OPT* and *KISSsoft* packages. The resulting solution can be used for the subsequent construction of the 3D computer model and further research.

Table 2 – Minimum values of criteria and required parameters of p.5 (the 1st numeric string) and of p.23 (the 2nd numeric string) when identifying the gear pump

Criteria					Required parameters		
F1da mm	***F2df*** mm	***F3V₀*** cm³	***F4X***	***F5ha****	h_f^*	j_n mm	***C*** mm
0,051	0,025	0,001	-0,007	-0,002	1,168	0,03	0,962
0,062	-0,02	0,089	-0,007	-0,001	1,169	0,03	0,979

Table 3 – Values of criteria and required parameters of the best solution

Criteria					Required parameters		
F1da mm	***F2df*** mm	***F3 V₀*** cm³	***F4 X***	***F5ha****	h_f^*	j_n mm	***C*** mm
0,055	-0,005	0,03	-0,007	-0,002	**1,363**	**0,03**	**0,975**

Table 4 – Result of gearing parameters calculation

Parameter designation	Mathematical model	Parameter designation	Mathematical model
d_a, mm	69,454	h_a^*	***1,168***
d_b, mm	51,684	m, mm	5
d_f, mm	45,395	d_w, mm	58,4
d, mm	55	J_n, **mm**	***0,03***
a_w, **mm**	***58,4***	C, mm	0,975
α_w, ^{0}	27,75	Z	***11***
X	***0,4025***	α, ^{0}	***20***
$X_{\min}$	0,2748	h_f^*	***1,363***
H, mm	12,03	*Pt*	14,76
S_a, mm	1,262	ϑ_P	-4,812
ε_α	1,301	W_K, mm	24,288
ρ	***0,38***	***b*, mm**	***38***

Table 5 – Criteria values in the KISSsoft protocol

F1da mm	***F2df*** mm	***F4 X***	***F5ha****
0.016	0,034	-0,0036	-0,002

Table 6 – Result of gearing parameters calculation

Parameter designation	Program *KISSsoft*	Parameter designation	Program *KISSsoft*
d_a, mm	69,416	h_a^*	1,168
d_b, mm	51,683	m, mm	5
d_f, mm	45,434	d_w, mm	58,4
d, mm	55	J_n, mm	0,034
a_w, mm	58,4	C	0,975
α_w, °	27,75	Z	11
X	0,4064	α, ^{0}	20
$X_{\min}$	absent in protocol	h_f^*	1,363
H, mm	11,991	*Pbt*	14,76
S_a, mm	1,294	ϑ_P	-4,761
ε_α	1,297	W_K, mm	24,301
ρ	0,38	b, mm	38

Conclusions. 1. The review of the works shows that the parametric identification tasks are being solved in many branches of science and technology, and mainly in the direction of increasing the adequacy of the mathematical model to the real object. However, in practice there are issues when the technical documentation of the object does not have some input data according to which it was designed and which are needed, for example, to construct a computer 3D model as well as to conduct further research. Another situation also arises: it is necessary to determine the parameters (basically gaps) in hard-to-reach places of the real object. In these cases, inverse problems of parametric identification arise, when we determine unknown parameters of the object by using the most reliable models. The experimental gear pump with a transparent casing, developed in the "Wrocław Polytechnica", is considered as such an object.

2. The proposed mathematical model for a gear pump includes the following:

- equations of foreign and domestic researchers of mechanical transmissions gearing;
- additional equations (of working volume, coefficient of profile shifting, rigid requirements to the coefficient of overlap, etc.) taking into account the peculiarities of the gearing in the pumping unit of the gear pump;
- parametric and functional constrains;
- criteria of adequacy and criterial constrains of the real object to its mathematical model (according to the values of the tip and root diameters, profile shifting coefficient, etc.) that makes it possible to set and solve the inverse tasks of multi-criteria identification.

3. The inverse task of multi-criteria identification is set and solved by the definition of three unknown parameters (h_f^*, J_n, C) for the experimental gear pump. This task is characterized by the following stages:

- correlation analysis of the assigned criteria (with parametric and functional constrains included);
- the introduction of criteria limits and the search for a nonempty set *D* with the definition of limit values (and the number of points) for each criterion and the identification of precedents for the best solution;
- local identification with the selected precedent and completion of the search for three unknown parameters;
- transfer of results for 3D computer model construction and for further investigation of internal hydrodynamics.

4. The performed calculations of the gearing geometry of the best solution with using the proposed MM and the dialog program *OPT* with the result of *KISSsoft* program calculation confirmed the proximity of the models and sufficient accuracy for practice.

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