Multicriteria Optimization of Spindle Units

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The quality of precision spindle units (S/Us) running on rolling bearings depends strongly on their structural parameters, such as the configuration and geometry of the S/U elements and bearing preloads. When S/Us are designed, their parameters should be optimized to improve the performance characteristics. However, it is practically impossible to state perfectly a general criterion function for S/U quality. Therefore, we propose to use a multicriteria optimization based on the parameter space investigation (PSI) method. We demonstrate the efficiency of the proposed method using the optimization results of high-speed S/Us.

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1. Introduction

Optimization in engineering essentially consists of multiparameter and multicriteria problems (Statnikov, 1999). In general, these problems cannot be reduced to single-criterion problems. When improving one performance characteristic of a given machine, we often cause another characteristic to deteriorate. That is why optimization problems are defined using a feasible set of structural parameters that will satisfy the stated criteria and constraints. From this set, we can find a subset of so-called Edgeworth-Pareto (EP) optimal (compromise) design variants, but it is impossible to improve all the criteria simultaneously (Statnikov and Matusov, 1995). In order to state and solve optimization problems successfully, a designer must first determine the feasible solution set. This set consists of the structural parameters that provide the sufficiently high performance characterristics desired of a machine. Mathematically, this condition can be represented in the form of constraints (Zverev, 1998). If a feasible solution set is not determined, the optimization algorithm may start searching for an optimal solution from solutions that are far from the best one.

In this paper, we present a new concept for searching for optimal design solutions for multicriteria optimization problems of spindle units (S/Us). To state and solve the optimization problems, we apply the parameter space investigation (PSI) method, which is currently used in different fields of industry, science, and technology (Steuer and Sun, 1995). In all these fields, the PSI method has been highly efficient (Stadler and Dauer, 1992). The PSI method is original and has no analogues (Dyer et al., 1995). It considers the major specific features of optimization in engineering and provides an opportunity to determine a feasible solution set for an arbitrary number of criteria (Lieberman, 1992), to choose the EP optimal solutions, to determine the correlations between the criteria and design variables, and to improve a mathematical model of the object to be designed, if necessary (Ozernoy, 1988).

2. Statement and solution of optimization problems

2.1 Multicriteria design of spindle units

A general algorithm for the multicriteria design of S/Us is presented in Fig. 1. When we start to develop a S/U, we first analyze the required accuracy, power consumption, kinematics, and other technical data. The computer-aided preparation of the data and referencing the database of technical solutions is included in Block 1 of the flow chart. Next, we look for solutions that satisfy the requirements of the S/U. The statement of the multicriteria design problem (Block 2) includes a statement of the requirements of the S/U characteristics (accuracy, stiffness, lifetime, etc.) within the constraints imposed on the S/U dimensions, parameters of operation, and manufacturing technology. If there is no suitable solution (Block 3), we start a preliminary search for spindle dimensions and types of spindle drives and bearings using our design procedures and referencing the database of standard S/U elements.

The multicriteria optimization of S/Us is performed in Block 4 of the flow chart. Since it is practically impossible to define a general criterion function for S/U quality, it is expedient to use optimization methods based on investigations of the parameter space using random or regular sequences (Dyer et al., 1995). The PSI method makes it possible to determine a feasible solution set that satisfies the given constraints for a structure (Statnikov, 1999). If the feasible set is not empty, a designer chooses the preferable S/U variant by matching additional requirements (low cost, adaptability to manufacturing, *etc.*). To apply the PSI method, we used the Multicriteria Optimization and Vector Identification (MOVI) software (Statnikov and Matusov, 1995) and a mathematical model of S/Us (Zverev and Push, 2000). The parameters of the S/U prototype can be determined using synthesis and optimization procedures (Blocks 3 and 4). This is followed by construction and tests of the prototype (Blocks 6 – 8). If the S/U characteristics satisfy the design criteria (Block 9), the design process is finished and the solution is added to the database.

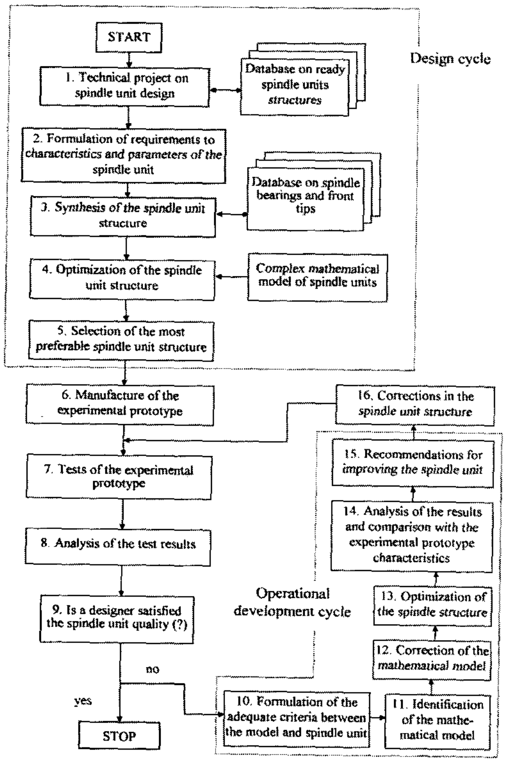

Fig. 1 S/U design and development flow chart

The results of the design process are based on optimizing an S/U mathematical model, whose adequacy has not yet been proven. Therefore, at this stage, mistakes are possible, and will be seen later while testing the prototype (Blocks 6 – 8). The purpose of the operational development is to detect and eliminate mistakes and discrepancies in the design phase. We do this by identifying the S/U mathematical model (Blocks 10 and 11) using the results of experimental tests (Block 7). The optimization results of the corrected model (Blocks 12 and 13) give us an opportunity to specify or reconsider the results obtained earlier (Block 14). Thus, we have an opportunity to issue reasonable recommendations for prototype improvement (Block 15) and to change the S/U structure (Block 16).

2.2 Multicriteria optimization of spindle units

The statement and solution of an optimization problem includes the following steps: 1) determine the design variables (optimization parameters); 2) state the optimization criteria and develop a mathematical model to estimate these criteria; 3) state the design variables, criterion, and functional constraints; and 4) choose the optimization method to search for a feasible set of design solutions.

In practice, we cannot define a general criterion function for S/U quality. However, we can apply the PSI method, which is based on parameter space investigation using uniformly distributed P_τ sequences (Statnikov and Matusov, 1996). This method has a number of advantages over other methods: 1) it does not require an analytical expression for the criterion function, 2) it provides high uniformity of parameter space investigation and the simplicity of its algorithms for calculating trial point coordinates is remarkable, 3) it is possible to find a global optimum of the criterion function, and 4) it makes it possible to determine the influence of the optimization parameters on the criteria.

Let us consider the main stages of the statement and solution of an optimization problem encountered during the design of a S/U. Suppose that the S/U quality depends on r design variables, $\alpha_1, \alpha_2, \ldots, \alpha_r$, representing the point (vector) $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_r)^T$ in r-dimensional space. The S/U structural parameters are the design variables that are to be optimized. The S/U optimization criteria determine the accuracy, lifetime, stiffness, reliability, cost, *etc.* These criteria, designated by $\Phi_v(\alpha)$ ($v = 1, 2, \ldots, k$), must be minimized or maximized. Generally, during the design phase, we must consider the design, functional, and criterion constraints. Design-variable constraints have the form:

$$\alpha_j^* \le \alpha_j \le \alpha_j^{**}, \qquad j = 1, \ldots, r \tag{1}$$

where α_j^* and α_j^{**} represent the boundary values of the S/U element dimensions. The functional constraints can be expressed as follows:

$$C_i^* \le f_i(\alpha) \le C_i^{**}, \quad i = 1, \ldots, t \tag{2}$$

where $f_i(\alpha)$ are functions of the design variables, *i.e.*, constraints that determine the S/U serviceability; and C_i^* and C_i^{**} are the lower and upper admissible values of the quantity $f_i(\alpha)$. We can also state the particular criterion constraints:

$$\Phi_v(\alpha) \le \Phi_v^{**}, \quad v = 1, \ldots, k \tag{3}$$

where Φ_v^{**} are the extreme values of the criteria (Φ_v^{**} is the worst value of criterion Φ_v that a designer may agree to accept). The constraints given by (1) produce a parallelepiped Π in r-dimensional space of the design variables. In turn, the constraints given by (2) produce the subset G in Π. Constraints (1) – (3) jointly produce the feasible solution set D, *i.e.*, the set of design solutions (α^j) that satisfy the constraints, and hence $D \subset G \subset \Pi$. If functions $f_i(\alpha)$ and $\Phi_v(\alpha)$ are continuous in Π, then sets G and D are closed (Sobol and Statnikov, 1981). The basic problem of multicriteria optimization is to find a set $P \subset D$ for which:

$$\Phi(P) = \underset{\alpha \in D}{extr}\,\Phi(\alpha) \tag{4}$$

where $\Phi(\alpha) = \{\Phi_1(\alpha), \Phi_2(\alpha), \ldots, \Phi_k(\alpha)\}^T$ is the criterion vector and P is the EP optimal set. The vector $\alpha^0 \in P$ can be determined from the solution of this problem. This is the preferable vector from set P. In many cases, set P is not too large (it may consist of several vectors only), and therefore it is not difficult to choose the preferred solution.

The PSI method can be divided into three stages. In the first stage, we investigate the parameter space and compile the test tables. First, we choose N trial points $\alpha^1, \ldots, \alpha^N$, uniformly distributed in subset G. Then, we calculate the criteria $\Phi_v(\alpha^j)$ at each point α^j and compile a test table for each criterion, arranging the values of $\Phi_v(\alpha^1), \ldots, \Phi_v(\alpha^N)$ in increasing or decreasing order (for criterion maximization or minimization, respectively):

$$\Phi_v(\alpha^{i_1}) \le \Phi_v(\alpha^{i_2}) \le \ldots \le \Phi_v(\alpha^{i_N}), \quad v = 1, \ldots, k \tag{5}$$

where $i_1, i_2, \ldots, i_N$ are the numbers of trials (a separate set for each v), and k tables jointly form a complete test table. The $P\tau$ sequences that are uniformly distributed in parameter space are used when choosing the trial points α^j. A systematic, comprehensive description of the mathematical properties of $P\tau$ sequences can be found in

Statnikov and Matusov (1996). The conditions given by (2) are checked when setting $\alpha = \alpha^i$. If the conditions are satisfied, we choose point $\alpha = \alpha^i$ as a trial point and calculate all the criteria $\Phi_v(\alpha^i)$ for it; otherwise, we reject the point. When defining the number of trial points N, it is necessary to consider the borders of variation of the design variables, the behavior of the criteria, and the time required for the criteria calculations. The formula by Sobol and Statnikov (1981) can be applied to define the lower value of N_{min}:

$$N_{min} = 2^{2+int(R)} \quad (6)$$

where R is the number of design variables and $int(\cdot)$ signifies calculation of the number integer part.

In the second stage of the PSI method, we truncate the test tables (5) following the constraint criteria Φ_v^{**} according to the S/U characteristic requirements.

In the third stage, we verify the solvability of problem (4) on a computer. In doing this, we assume that criterion $\Phi_{v_1}(\alpha)$ is fixed and consider the corresponding table (5). Let $s = s(v_1)$ be the number of values in the table satisfying the chosen criterion constraint:

$$\Phi_{v_1}(\alpha^{i_1}) \le \ldots \le \Phi_{v_1}(\alpha^{i_s}) \le \Phi_{v_1}^{**} \quad (7)$$

Sorting the values $\Phi_v(\alpha^{i_1}),\ldots,\Phi_v(\alpha^{i_s})$ for all v, we can check whether there is at least one point among $\alpha^{i_1},\ldots,\alpha^{i_s}$ in which all inequalities (3) are valid simultaneously. If we find at least one point, the set D defined by inequalities (1) – (3) is nonempty, and problem (4) is solvable. Otherwise, we must return to stage 2 and make certain concessions in the specification of Φ_v^{**}. Conversely, if the S/U quality concessions are undesirable, we can return to stage 1 and increase N in order to repeat stages 2 and 3 using extended test tables. As a result, we can find a feasible solution set D and an EP optimal set P, formally and analyze them informally, and choose a preferable S/U structure.

Definition: The point $\alpha^{EP} \in D$ is an Edgeworth-Pareto optimal point if there exists no point $\alpha \in D$ in which $\Phi_v(\alpha) \le \Phi_v(\alpha^{EP})$ for all $v = 1, \ldots, k$ and $\Phi_{v_0}(\alpha) \le \Phi_{v_0}(\alpha^{EP})$ for at least one $v_0 \in \{1, \ldots, k\}$. The set $P \subset D$ is the Edgeworth-Pareto optimal set if it consists of the EP optimal points. The importance of this set is determined using the theorem stated in (Sobol and Statnikov, 1981).

Theorem: If the feasible solution set D is closed and the criteria Φ_v are continuous, then the EP optimal set P is nonempty. Therefore, when solving a multicriteria optimization problem, we must always determine a set of EP optimal solutions.

Let us consider the construction of the feasible solution set for a simple case. We assume that the quality of the machine can be estimated using criteria Φ_1 and Φ_2, which depend on the design variables α_1 and α_2 (Fig. 2). We wish to minimize the criteria.

We also assume that a sufficiently large number of design solutions α^i and $\Phi(\alpha^i)$, where $i = 1, \ldots, N$, can be generated by a computer (as plotted in Fig. 2a and b with dots). In Fig. 2b, $\Phi(\alpha^i)$ is the image of α^i in the criterion space. Because of the three functional constraints, and (Fig. 2c), the initial set of solutions decreases. In Fig. 2c, the domain $G \subset \Pi$ satisfies the functional constraints. Within the criterion space shown in Fig. 2d, $\Phi(G)$ is the image of G, so that , $i = 1,2,3$. Having determined G, we can search for the set of feasible solutions D. In Fig. 2f, we illustrate three dialogues. The first one is represented by and , where the second subscript indicates the number of the dialogue and $D_1 = \varnothing$. At this stage, we can make a concession. The second dialogue is represented by and, and $D_2 = \varnothing$. The third dialogue is represented by and ; here $D_3 \neq \varnothing$, $D_3 \subset G$. In Fig. 2e, and are the inverse images of and in the design variable space. In Fig. 2f, $\Phi(P)$ is the set of EP optimal solutions in the criterion space. The ratio γ of the volume D to the volume of the initial parallelepiped Π can be too small ($\gamma < 0.1$) to consider the values of the functional (2) and criterion (3) constraints that exist in practice.

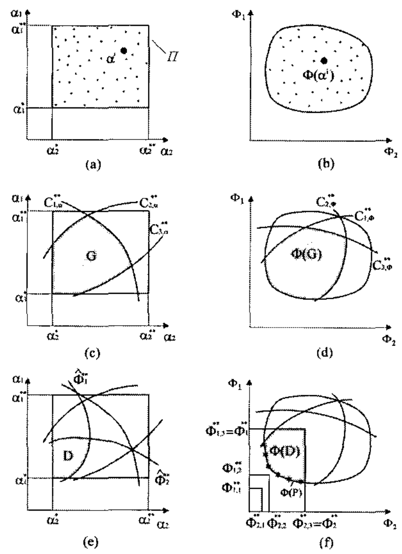

Fig. 2 Example of the feasible set (D) construction

3. Examples of multicriteria optimization of spindle units

S/Us are the principle units in machine tools since they determine the accuracy and productivity of the machining process. Currently, most S/Us used in the machine tool industry run on rolling bearings because the bearings are cheap, reliable, and simple to operate and maintain. We consider two examples of S/U optimization: the S/U of a lathe and S/U of a grinding machine.

3.1 Spindle unit of a lathe

We used the following parameters for the lathe S/U: maximum rotation speed of 4,500 rpm and maximum radial and axial cutting loads $P_R^{max} = P_A^{max} = 2{,}500$ N. The design variables and constraints of the S/U are listed in Table 1, where d_o is the diameter of the inner hole in the spindle, t_s is the thickness of the spindle wall at the front bearing, and α_3^{min} and α_3^{max} are the values of light and heavy bearing preloads.

Table 1 Design variables and constraints for the lathe spindle unit

Design variables	Design constraints	
	Minimum	Maximum
Distance between the bearings (α_1), mm	$\alpha_1^{min} = 160$	$\alpha_1^{max} = 360$
Outer diameter of the spindle (α_2), mm	$\alpha_2^{min} = d_o + 2 \cdot t_s$	α_2^{max} (limited by bearings' speed-limit factor)
Preload of the bearings (α_3), N	$\alpha_3^{min} = 500$	$\alpha_3^{max} = 2{,}400$
Thickness of the housing walls (α_4), mm	$\alpha_4^{min} = 10$	$\alpha_4^{max} = 30$

The optimization and constraint criteria, which were based on the S/U prototype characteristic requirements, are presented in Table 2. The stiffness constraints were obtained by analyzing the balance of the machine tool stiffness presented in its technical specifications. The following conditions were accepted as the functional constraints:

$$P_R^{max} < P_R^L = f_1(\alpha_3)$$
$$P_A^{max} < P_A^L = f_2(\alpha_3) \qquad (8)$$

Therefore, the maximum radial P_R^{max} and axial P_A^{max} loads on the S/U (see Fig. 3b) must not exceed the limit loads P_R^L and P_A^L, respectively, which are dependent on the bearing preload α_3. If these conditions are not met, the balls in the front bearing will lose contact with the races, and the S/U operation will become unstable.

Table 2 Optimization and constraint criteria for the lathe spindle unit

Criteria	Criterion constraints
Speed-limit factor of the bearings (Φ_1), mm·rpm	$\Phi_1 \leq 0.45 \cdot 10^6$
Radial stiffness of the spindle unit (Φ_2), N/µm	$\Phi_2 \geq 300$
Radial run-out of the spindle (Φ_3), µm	$\Phi_3 \leq 3.0$
Temperature of the bearings (Φ_4), °C	$\Phi_4 \leq 40$

The optimization was performed using finite beam element models of the S/Us (Zverev and Push, 2000). A diagram of the model is shown in Fig. 3. Following the PSI method, we performed 1024 trial tests in which we estimated the criteria Φ_ν ($\nu = 1, ..., 4$) in the space of the design variables ($\alpha_1, ..., \alpha_4$). As a result, we determined 46 S/U variants that satisfied all the constraints. The feasible solution set D is plotted on the plane of the principle design variables α_1 and α_2 in Fig. 4.

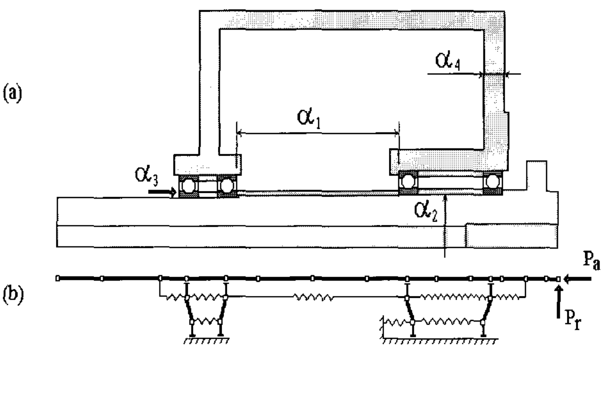

Fig. 3 Structural (a) and analytical (b) diagrams of the lathe spindle unit

The EP optimal solutions corresponded to the combinations of the design variables at which only one of criteria Φ_ν could be improved, but at the expense of the others. The set D consisted of points for which all the criteria could be improved simultaneously if they were moved into the set of compromise solutions.

The normalized criteria λ_ν ($\nu = 1, ..., 4$) of the seven EP optimal variants are given in Table 3. The values λ_ν were derived from $\lambda_\nu = \Phi_{max}/\Phi_i$ if criterion Φ_ν was to be maximized, and from $\lambda_\nu = \Phi_i/\Phi_{min}$ if criterion Φ_ν was to be minimized. Here, Φ_{max}, Φ_{min}, and Φ_i are the maximum, minimum, and current values of criterion Φ_ν in the column, respectively. The parameter λ_ν characterizes the proximity of the variant to the best solution, for which $\lambda_\nu = 1$. From a formal analysis of Table 3, it follows that the best variant was number 49 (α_1 = 233.1 mm, α_2 = 100.0 mm, α_3 = 1330.4 N, and α_4 = 28.6 mm), for which the value of $\sum\lambda_\nu$ was a minimum.

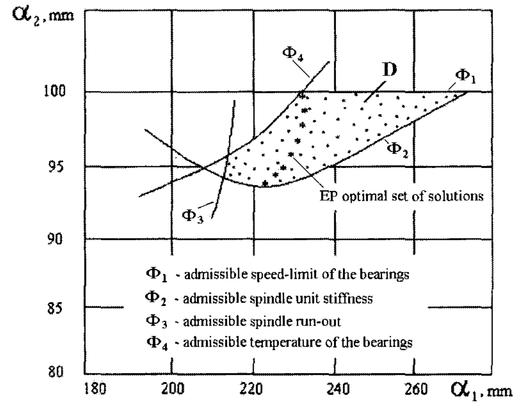

Fig. 4 Feasible solution set (D) and EP optimal set

Generally, the final decision in favor of one or another variant can be made after considering additional informal reasons, such as adaptability to manufacturing and costs. In the examples under consideration, we tried to optimize the S/Us of the given structures. The choice of the optimal S/U structure (structural optimization) was made from a comparative analysis of the criteria of various structures having optimal parameters.

Table 3 Normalized criteria of the EP optimal variants of the lathe spindle unit

Variants	Normalized criteria λ_ν				
	λ_1 (maximized)	λ_2 (maximized)	λ_3 (minimized)	λ_4 (minimized)	$\sum\lambda_\nu$
8	1.03	1.16	1.05	1.14	4.38
49	1.0	1.05	1.02	1.07	4.14
176	1.06	1.37	1.03	1.20	4.66
203	1.01	1.0	1.08	1.28	4.37
454	1.04	1.22	1.0	1.23	4.49
793	1.07	1.43	1.12	1.0	4.62
941	1.02	1.12	1.01	1.03	4.18

3.2 High-speed spindle unit of a grinding machine

We used the following parameters for the grinding machine S/U: maximum rotation speed of 24,000 rpm and maximum radial cutting load P_R^{max} = 50 N. The bearing preload was adjusted using the air pressure supplied (see Fig. 5a).

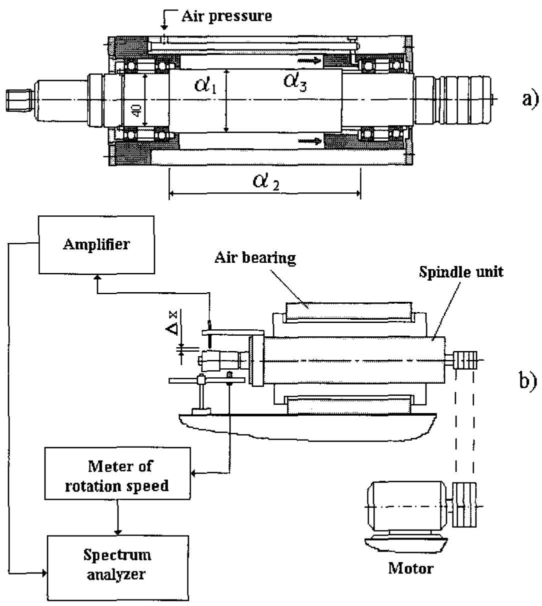

Fig. 5 Grinding spindle unit (a) and layout of the experimental rig (b)

The S/U prototype α^{pr} had the following parameters: $\alpha_1 = 47$ mm, $\alpha_2 = 315$ mm, and $\alpha_3 = 500$ N. The design variables and constraints of the S/U are listed in Table 4.

Table 4 Design variables and constraints for the grinding spindle unit

Design variables	Design constraints	
	Minimum	Maximum
Diameter of the spindle (α_1), mm	$\alpha_1^{min} = 44$	$\alpha_1^{max} = 56$
Distance between the bearings (α_2), mm	$\alpha_2^{min} = 200$	$\alpha_2^{max} = 380$
Preload of the bearings (α_3), N	$\alpha_3^{min} = 350$	$\alpha_3^{max} = 750$

The optimization criteria and appropriate criterion constraints, which were stated based on the S/U prototype characteristic requirements, are given in Table 5.

Table 5 Optimization and constraint criteria for the grinding spindle unit

Criteria	Criterion constraints
Radial stiffness of the spindle (Φ_1), N/μm	$\Phi_1 \geq 16$
Fatigue lifetime of the bearings (Φ_2), hr	$\Phi_2 \geq 5{,}000$
Radial run-out of the spindle (Φ_3), μm	$\Phi_3 \leq 2.5$
Radial accuracy of rotation of the spindle (Φ_4), μm	$\Phi_4 \leq 1.0$
The 1st frequency of spindle bending natural oscillation (Φ_5), Hz	$\Phi_5 \geq 600$
Temperature of the bearings (Φ_6), °C	$\Phi_6 \leq 40$

The following condition was accepted as the functional constraint:

$$P_R^{max} < P_R^L = f(\alpha_3) \quad (9)$$

Therefore, the maximum radial load P_R^{max} must not exceed the limiting load P_R^L, which is dependent on the bearing preload α_3. When the bearing preload is too low, it can create loose contacts between the ball bearing and races and introduce instability. Following the PSI method, we performed $N = 1024$ trial tests in which we estimated the criteria Φ_ν ($\nu = 1, ..., 6$) in the parallelepiped Π^1 that was produced by the design variable constraints in the space of the design variables ($\alpha_1, ..., \alpha_6$). A total of 120 trials were rejected because of constraint (9). The dependence of the criteria on the design variables is shown in Fig. 6.

As a result, we determined 38 variants, one of which was the EP optimal solution that simultaneously satisfied all the constraints and formed the feasible set D. Then, once we analyzed the histograms showing the design variable distribution and interrelation between the design variables and the criteria, we constructed and analyzed a new parallelepiped Π^2 $(\Pi^2 \subset \Pi^1)$ in order to improve the results, and repeated 256 trials. This produced 52 feasible vectors that met all the constraints. One of these vectors was the EP optimal α^{EP} with the following parameters: $\alpha_1 = 48$ mm, $\alpha_2 = 310$ mm, and $\alpha_3 = 460$ N. Additional computations demonstrated that increasing the number of trial points in parallelepiped Π^2 from 256 to 512 did not expand set D by more than by 4 – 5%, and no new EP optimal variants with the better criteria values were obtained.

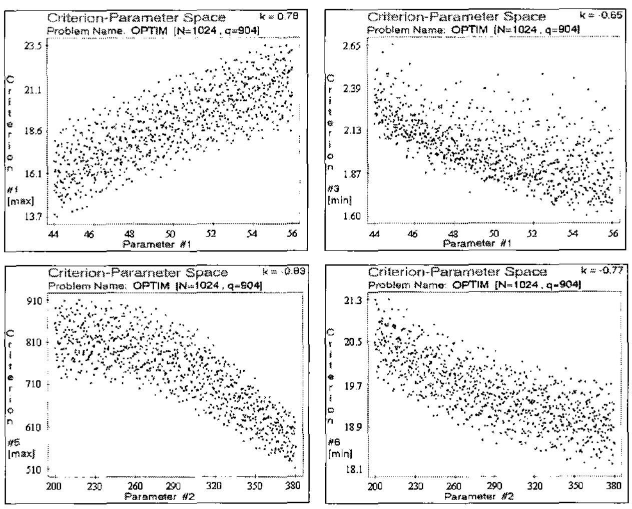

Fig. 6 Dependence of the design criteria on the parameters (design variables)

In order to demonstrate the accuracy of the method and models used, we conducted experimental tests and determined the criteria (except criterion Φ_2) of the prototype and EP optimal S/U. The layout of the experimental rig used for testing the high-speed S/Us is shown in Fig. 5b. The S/U housing was mounted in the aerostatic bearing to isolate the S/U from the bed.

The spindle radial stiffness (criterion Φ_1) was measured by checking the radial clearance Δ_x between the contactless sensor (model TRK/2-5, Hettynger) and the surface of the measuring mandrel. A signal from the sensor passed through the amplifier (KWS-73, Hettynger) to the spectrum analyzer (Model 2031, B&K). The measuring system sensitivity was 0.1 μm. The run-out and accuracy of the spindle rotation (criterions Φ_3 and Φ_4) and the natural frequency of spindle oscillation (criterion Φ_5) were measured with a contactless sensor (WSG-69-5, Roitlinger) equipped with an amplifier (WSM-6983, Roitlinger). The stabilized temperatures of the spindle bearings (criterion Φ_6) were measured using a digital contact thermal probe (SKF) with an accuracy of 1°C.

The estimated and experimental values of the criteria are presented in Table 6. The maximum difference between the estimates and measurements reached 15.4% (criterion Φ_4), which is acceptable. If we were to improve the prototype based on the EP optimal S/U, the major performance criteria would increase by 7.1% (criterion Φ_5) to 54% (criterion Φ_4). This demonstrates the efficiency of the multicriteria S/U optimization.

Table 6 Performance criteria for the prototype and EP optimal variant

Criteria	Prototype			EP optimal variant		
	Sim.	Exp.	Rel. error,%	Sim.	Exp.	Rel. error, %
Φ_1, N/μm	15.2	14.7	3.4	17.3	16.5	4.8
Φ_2, hr	6280	-	-	7128	-	-
Φ_3, μm	2.27	2.40	10.2	1.86	2.00	7.0
Φ_4, μm	0.89	1.0	11	0.55	0.65	15.4
Φ_5, Hz	671	655	2.4	729	705	3.4
Φ_6, °C	39.1	40	2.3	35.6	37	3.8

4. Conclusions

The results of this study may be summarized as follows.

1. An algorithm for multicriteria optimization of S/Us based on the parameter space investigation method was developed using the program MOVI to implement the PSI method and the Zverev and Push model to estimate the performance criteria of S/Us.
2. The main stages of the multicriteria optimization were demonstrated using the S/Us for a lathe and a high-speed grinding machine. The feasible and EP optimal variants of the S/Us that satisfied the given criteria and constraints were obtained in the space of the design variables. Experiments showed good agreement with the theoretical results.
3. The multicriteria optimization presented a good opportunity to improve the performance of machining tools.

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