Reports on research projects

(2018), «EUREKA: Physics and Engineering»
Number 3

RATIONAL CHOICE OF TWO-SUPPORT SPINDLES FOR MACHINING CENTERS WITH LUBRICATION SYSTEM

Oleg Krol
Department of Machinery Engineering and Applied Mechanics
Volodymyr Dahl East Ukrainian National University
59-a Central ave., Severodonetsk, Ukraine, 93400
krolos.snu.edu@gmail.com

Petko Tsankov
Faculty of Engineering and Pedagogy
Technical University of Sofia, Bulgaria
59 Burgasko Schose str., Sliven, Bulgaria, 8800
ptsankov@abv.bg

Volodymyr Sokolov
Department of Machinery Engineering and Applied Mechanics
Volodymyr Dahl East Ukrainian National University
59-a Central ave., Severodonetsk, Ukraine, 93400
sokolov.snu.edu@gmail.com

Abstract

In the multivariate design mode, based on the effective parallel design facilities, the rational choice of the design of the two-support spindle for the machining center is the main aim of this article. A modified scheme for selecting a spindle unit is proposed, which reflects the procedure for the formation of its main components: "Representations on the Spindle Unit Variations" and "Representations on the Designer's preferences". A concept is introduced and a component of the selection scheme is described: "Procedural model", which makes it possible to realize the mechanism of forming preferences of the machine tool builder in the process of selecting the best design alternative. 3D models of the horizontal and vertical spindle heads for the multi-operation CNC machine are developed on the basis of the proposed modified scheme of rational choice. The analysis of various methods and technology of spindle units lubrication is presented and it is shown how the declarative (the most complete description of the methods and features of lubrication) representation in the selection of design priorities and the adoption of design solutions is used. The introduction of rational choice facilities into the practice of design activities in the field of machine tool building improves the efficiency of the multivariate design with a return character, significantly increasing the productivity of work and the quality of the design decisions.

Keywords: rational choice, spindle unit, lubrication system, declarative model, procedural model.

DOI: 10.21303/2461-4262.2018.00648

1. Introduction

The design problems associated with multi-iteration, recurring algorithm, multi-criteria led to the idea of "parallel construction as an alternative to a set of sequential acts of making design decisions". A systematic approach to design, incorporating the above procedures, underlies the modern methodology for creating machine tools.

The process of creating new machine-building products is characterized by the phenomenon of "permanent underdefinition" of the initial data array and techno-economic limitations of the basic design procedures. The need for additional definition makes the task of designing new products is search, which is based on methods and procedures for engineering forecasting of design and engineering solutions [1, 2]. To such design tasks can be attributed the task of designing the main shaping spindle units (SU) of machine tools.

The traditional approach to the design process as a sequence of acts for analysis, synthesis and decision-making faces a number of contradictions that lie at its base. These include procedures for the sequential analysis of the elements of the design, the formation of alternative options and the choice of the best.

In order to answer the question of choosing alternatives, the designer in fact solves another problem of choice, the result of which is the selection of the necessary selection criteria. Thus, the original logic is transformed into a modified selection scheme [1, 3]. The variety of production situations leads to a large number of alternative preferences and differences in priorities placed by the designer on this set. Further analysis of the selection process leads to a problem situation associated with the answer to the question: what kind of information is needed in the task of choosing preferences? The answer to this question can be given by the study of the alternatives properties themselves (variants of spindle unit designs).

Among the set of properties of the SU structures can be identified: the types and location of supports, the design and magnitude of the preliminary load in the supports, the system and method of lubrication,

In the general case, the set of properties characterizing the SU and influencing the selection process is “constructively large”. An attempt to limit the problem of choice by taking into account only essential properties comes up against the question: what are the preferences we are going to use. And the choice of these preferences is made on the basis of the selected properties analysis. Logically, the way out of this vicious circle is the rejection of implicit assumptions, both about independence and hierarchy of the relationship between the two components of choice [3]:

– representations about SU variants (declarative model);

– representations of the designer preferences.

Thus, in order to improve the problem of rational choice for the spindle unit design, the following statement of the problem is proposed. To develop a procedure for creating a set of design options for the SU on the basis of a set of representations on project alternatives, user aspects of application, system priorities. With this procedure, a reduction in the number of iterations of the design process and resolution of problems of recurrent nature will be realized. As a result: increase in the designer productivity and the quality of the design decisions.

2. Review of the problem

Along with the traditional approaches to the creation of a new SU project, there are works [4, 5] in which the modernized logic of the traditional design process is used. Its essence consists in parallelizing of design tasks, introduction of a modular principle and decomposition of a kind of design works. The use of a cyclic and parallel-cyclic design strategy involves the use of parallel and alternative stages and, as a consequence, a change in strategy in accordance with the results of previous stages [3].

At the same time, the improvement logic proposed above does not affect the interaction of generated project variants and efficiency criteria (priority system) for choosing a compromise version of the SU design.

For a spindle unit equipped with various instrumental adjustments, an approach [6] is proposed for setting and solving a variant techno-economic problem. This is essentially the task of choosing the most cost-effective combination of a structural variables set and parameters of a spindle unit with a modular tooling. At the next stage, the process parameters are selected taking into account the existing relationships, technical limitations and other relations. The complexity of such task is a consequence of the presence of a set of subtasks. They include the definition: the number and method of blanks location on the machine; types of bearing supports and the scheme of their mounting. In addition, pre-tensioning methods and its magnitude are taken into account; type of instrument and grade of instrumental materials.

Among the various approaches to solving this complex techno-economic problem, one can note the approach connected with its reduction to the problem of mathematical programming [6]. In the absence of analytical equations, the use of the random search procedure is allowed. The second approach involves the use of structural optimization of the iterative type [7], which includes: making decisions to improve the base variant, taking into account the results of parametric optimization for the permissible scheme of technological adjustment. Then the process of improvement is repeated for each next permissible setting option and the adoption of a subjective decision about the end of the design.

The third approach is focused on the transformation of the problem to a two-stage, non-optimized feasibility procedure using the considered SU design for a set of technological operations for processing housing-type parts. Such transformation [8] is possible only in the case of limiting the sizes of machines that implement drilling, drilling-out, core-drilling and reaming operations.

The main difference introduced by the authors into the traditional selection scheme consists in modifying the stage of forming the initial set of project variants, which is accomplished by incremental improvement of the original alternative based on the results of parametric optimization. The main methods of improving the considered SU variant are the changes in the options for duplexing bearing support, the choice of a design scheme for creating a pre-tension and the use of a more perfect lubrication system.

At the same time, the analysis of the choice logic inherent in these three approaches shows that they are mainly inserted in the traditional scheme for implementing the project procedure. In this case, the authors do not set themselves the task of selecting and pick out the espesial preferences necessary to determine the main criterion (criteria) for making design decisions. But in the case of setting the task of selecting espesial preferences, the designer encounters an interrelated task of research the properties of the alternatives themselves (SU constructions) and forming an array of information for solving the problem of choosing preferences.

3. Materials and methods

Spindle units of metal cutting equipment are the main forming units, predetermining the output quality and productivity of the designed machines and machining centers. In the practice of machine-tool construction there is a wide variety of SU designs for rolling bearings of various types [9–11]. One of the basic characteristics of the spindle is that the speed of the $d \cdot n_{max}$ should reach $(0.8...1.0) \cdot 10^6$ mm/min, the rotation error is less than 0.2...0.3 µm, the durability is not less than 5000 hours for especially high-speed and not less than 10,000 hour – for high-speed.

On the basis of the proposed methodology of rational choice [1] and the toolkit for implementing this methodology [12], a modified scheme for SU selection on the rolling-contact bearings is proposed (**Fig. 1**). In this case, the process of selecting project alternatives (SU variants of machine tools) consists in the parallel construction of such components for the selection scheme as “Representations on the Spindle Unit Variations” and “ Representations on the Designer’s preferences”. And the resolution of the contradiction [1, 3] between the system of preferences and the properties of the considered design options will be realized by entering the so-called “procedural” model. At the same time, the limitation of the task due to taking into account only the espesial properties is predetermined by the preferences that are formed at the previous stage of the selection (**Fig. 1**).

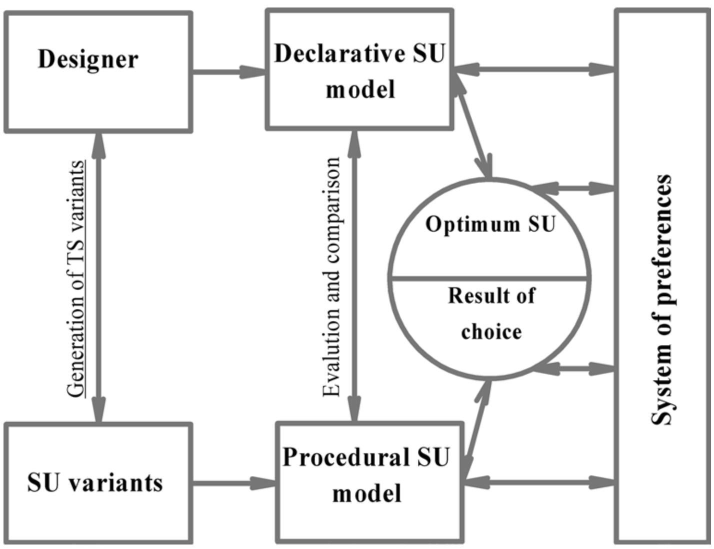

Fig. 1. Modified scheme for selecting project alternatives

In accordance with the scheme of rational choice, let's realize the formation of project variants based on the known 9 typical SU schemes [13]. At the initial stage of selecting the type of supports (rolling, sliding, hydrostatic, hydrodynamic, etc.), information is needed on the selection criteria that are determined depending on the characteristics of the various options at the levels of the declarative and procedural models. At this initial stage, declarative knowledge includes data on typical rolling bearing diagrams that are sufficient for constructing a procedural model. So for machining centers of a drilling-milling-boring group, the information requirements of the declarative model will be related to the requirements of the technical specification concerning rigidity (load-carrying capacity not less than $2 \cdot 10^4$ N). At the same time, the nominal durability should exceed 10,000 hours) and the speed should be $d \cdot n_{max}=(4.5...6.0) \cdot 10^5$ mm/min.

At the next step, a choice is made according to the direction of the action, perceived by the load. The combined nature of the loading of machining centers predetermines the use of radial-thrust bearings that take radial and axial loads. This makes it possible, at the stage of constructing a declarative model, to implement a series selection, for example BS, V, E-SE, ED of the SNFA standard. In this case, for these series, the specification of such characteristics of the supports as the number and nature of the placement is carried out. Throughout the designs of the machining centers, the "duplex", "triplex", "quartet" connection schemes, etc. are used. Another aspect of the analysis is the methods and values of the preload that are associated with the need to increase the SU stiffness. The increase in the initial set of design variants can occur due to the different type of mounting of bearing supports, choice of the method of lubrication and the type of seals.

Thus, at the first stage of rational choice, a multi-step procedure for the formation of project alternatives is implemented, and in the formation of which there is no need to use quantitative estimates. At the same time, it is necessary to take into account forbidden combinations at this stage, for example the mounting of "duplex-tandem" supports from various bearings, etc. The identification of forbidden combinations is realized by the interaction of two components of the rational choice scheme (**Fig. 1**): «Spindle unit variants» – «System of preferences».

4. Experiments

On the basis of the developed sequence of rational choice steps, promising designs of high-speed SU for the multi-operation machine type SF68VF4 (drilling-milling-boring machine with CNC) are developed [14–16]. A feature of this machine is a detailed developed modular tooling, including horizontal and vertical spindle heads. **Fig. 2, 3** show the three-dimensional models of the horizontal and vertical spindle heads developed by the authors, respectively [17].

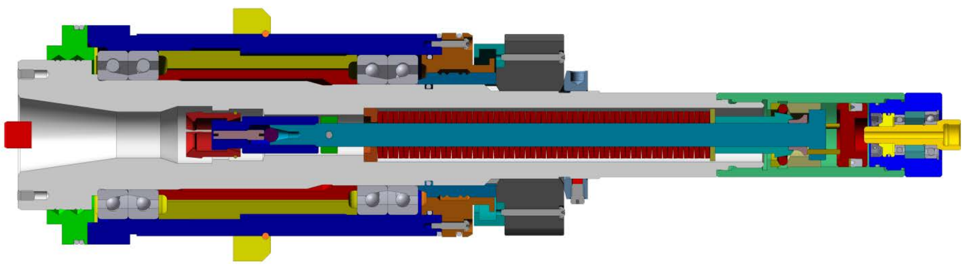

Fig. 2. Horizontal spindle head of machining center

The spindle (**Fig. 2**) is mounted on double radial-thrust bearings, duplexed according to the tandem scheme, characterized by the following values:

– axial deflection δ_{aT}=5.9 microns, corresponding to the pre-loading force P_H=460 H;

– the axial rigidity of the symmetrical support $j_{aT}=3{,}7 \cdot 10^5$ N/mm. At the same time, the achievable axial stiffness is 10 % higher than the DX scheme;

– the total axial strain (preload), equal to Δ_T=0.0074 mm;

– the magnitude of the speed, which increases to $d \cdot n_{max.}$=26000 mm/min; $d_{av} \cdot n_{max.}$= =330,000 mm/min.

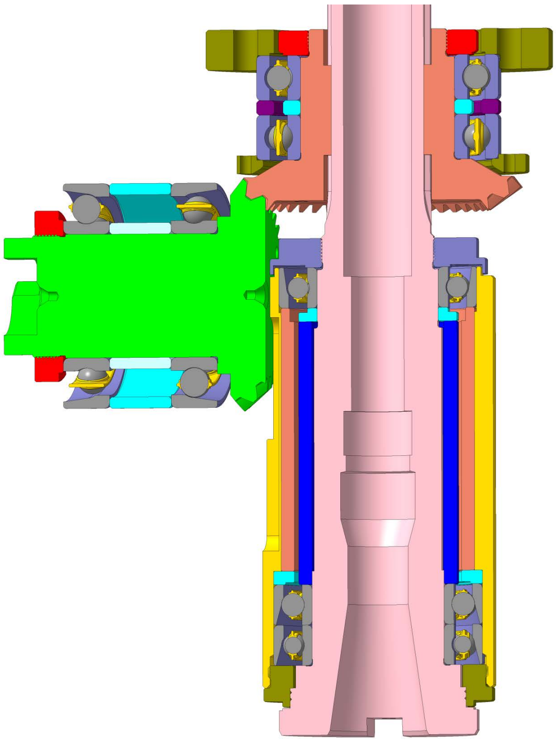

Fig. 3. 3D model of the vertical spindle head

As noted above, the formation of the full design variants that form the basis of the declarative model in the rational choice procedure is impossible without determining the method and design of support lubrication as one of the espesial properties [17–19]. At the stage of primary formation for design alternatives, possible methods of lubrication are considered. Not all these methods are applicable in the construction of high-precision high-speed machines.

The above values of high speed make it possible to make judgments about the applicability of the lubrication methods. So the liquid lubricant in the oil bath is limited to $d_{av}·n_{max}$=100000 mm/min, which is unacceptable. On the other hand, methods such as oil injection, minimum drip lubrication and oil mist are applicable at high speeds $d_{av}·n_{max}$=≥750000 mm/min.

In the calculated design limits, the circulating lubricant (natural and forced) is mainly used, which ensures the lubricant flow required by the condition of the heat sink through the bearing [20].

Along with liquid, greases are also used, which are limited by relatively small numbers of speed. So for the considered 46000 series angular contact bearings with contact angle 26^o, the maximum speed is in the range $d·n_{max}$=220000...320000 mm/min, which is suitable for this design variant $d·n_{max}$=26000 mm/min. The required volume of lubrication V, m^3 in accordance with the formula [21] is $V=1.49·10^{-4}$ m^3.

The choice of the type of lubricant, the location of the spindle unit and the operating conditions dictate the type of seal. So, with a horizontal spindle arrangement (**Fig. 2**), bearing grease and the labyrinth seals of a non-contact type are most often used. To protect the bearings under especially difficult conditions at low and medium speeds, the design is strengthened by a cup-type seal and, conversely, slot seals are used to protect SU operating under favorable (contaminated) conditions.

When the spindle is vertically positioned (Fig. 3), do not let oil from the upper bearing into the lower bearing. For this, a seal must be provided on the underside of each bearing, in addition to the drain. Otherwise, an excessive amount of oil in the lower bearings will lead to excessive friction losses and an increase in their temperature.

5. Results

The procedure of rational choice for two-support spindle units designs based on the idea of parallel construction is realized: a set of design alternatives, declarative and procedural models, a system of priorities and the result of choice. A peculiarity of this approach is the integration of the procedural model into the circuit of the SU selection process, which allows to concentrate information on promising variants of their designs.

An approach to the formation of a declarative model in the design of two-support spindle nodes is proposed, the structure of declarative knowledge is revealed, including typical rolling bearing schemes that limit the parameters of rigidity, nominal durability, specific speed and lubrication methods. It is shown that such minimal data composition at the initial stages of the design process will be sufficient for constructing a procedural model.

The choice of the type of lubrication has been made, depending on the location of the spindle unit and operating conditions, as well as the type of seal associated with it. Three-dimensional SU models with horizontal and vertical arrangement of a spindle are designed, which design provides effective lubrication of their details. The most espesial properties selected in the declarative model of two-support SU are selected, which, in the parallel design mode, which are used to ranking and select criteria for making design decisions.

Use of the toolkit of rational choice provides an effective procedure for multivariate design with a return character, making the process of analysis, synthesis and decision making purposeful.

6. Conclusions

As a result of the conducted researches the approach to perfection of the design process with reference to the problem of designing the main shaping spindle unit of machining centers is offered. This makes it possible to reduce the number of iterations of making design decisions by concurrently constructing alternate SU designs and a set of designer preferences (criteria for choosing the optimal solutions). At the same time, the connection of the object selection “Set of preferences” with the set of properties for the projected product, so-called “Declarative model of the object”. For products which nomenclature is constantly changing, but the dominant properties remain practically unchanged, this approach is of interest. It should be noted that the drawback of this approach is the complexity of the multi-step logic of decision-making, especially when solving the multivariate tasks of designing large engineering units.

This research is based on the methodology of rational choice in the machine tool industry, which was formulated and developed in previous works of the authors. It is oriented on a specific group of nodes that limit the competitiveness of machining centers, and focuses on the role of the lubrication system in the process of making rational design decisions. The plans of the authors outline the improvement of the rational SU selection procedure by means of setting and solving the multi-criteria optimization problem for structures taking into account the prospects for the development of multi-operational metal cutting equipment.

References

[1] Krol, O. S., Sokolov, V. I. (2017). Metody i procedury racional’nogo vybora v stankostroenii [Methods and procedures of rational choice in machine tool construction]. Lugansk: VNU, 112.

[2] Krol, O. S., Sokolov, V. I. (2017). Metody i procedury inzhenernogo prognozirovaniya v stankostroenii [Methods and procedures of engineering forecasting in machine tool building]. Lugansk: VNU, 114.

[3] Emel’janov, S. V., Nappel’baum, Je. L. (1981). Sistemy, celenapravlennost’, refleksiya [Systems, focus, reflection]. Sistemnye issledovaniya. Metodologicheskie problemy, 7–38.

[4] Puhovskij, E. S. (1991). Matematicheskoe modelirovanie processa tehnologicheskogo proektirovaniya stanochnyh sistem [Mathematical modeling of process of technological design of machine systems]. Tehnologiya i avtomatizaciya mashinostroeniya, 47, 77–87.

[5] Aver’janov, O. I. (1987). Modul’nyj princip postroeniya stankov s ChPU [Modular principle of building CNC machines]. Moscow: Mashinostroenie, 232.

[6] Temchin, G. I. (1957). Teoriya i raschet mnogoinstrumental’nyh naladok [Theory and calculation of multi-instrumental adjustments]. Moscow: Mashgiz, 556.

[7] Gil’man, A. M., Gostev, G. V., Egorov, Ju. B., Jasanov, Ju. V. (1957). Avtomatizirovannoe proektirovanie optimal’nyh naladok metallorezhushhih stankov [Automated design of optimal settings for metal-cutting machines]. Moscow: Mashinostroenie.

[8] Basin, Ju. Ja., Korol, I. V., Rozental‘, P. L. (1985). Avtomatizirovannoe proektirovanie instrumental’nyh naladok na JeVM [Automated design of instrumental adjustments on a computer]. Stanki i instrument, 2, 3–4.

[9] Push, V. Je. (1985). Metallorezhushhie stanki [Metal-cutting machine tools]. Moscow: Mashinostroenie, 256.

[10] Pronikov, A. S., Borisov, E. I., Bushuev, V. V. et. al. (1995). Proektirovanie metallorezhushhih stankov i stanochnyh sistem [Design of metal-cutting machine tools and machine system]. Moscow: Mashinostroenie, 320.

[11] Yoshimura, M. (1984). Multiobjektive design optimization of mashine-tool spindles. Transactions of the ASME, 48–53.

[12] Krol, O. S. (1997). Instrumental’nye sredstva racional’nogo vybora tehnologicheskih sistem mehanoobrabotki [Instrumental means of rational choice of technological systems of machining]. Vestnik NTUU (KPI), 32, 157–161.

[13] Bal’mont, V. B., Gorelik, I. G., Figatner, A. M. (1987). Raschety vysokoskorostnyh shpindel’nyh uzlov [Calculations of high-speed spindle nodes]. Moscow: VNIITEMR, 52.

[14] Shevchenko, S., Mukhovaty, A., Krol, O. (2017). Gear Clutch with Modified Tooth Profiles. Procedia Engineering, 206, 979–984. doi: 10.1016/j.proeng.2017.10.581

[15] Krol, O. S., Burlakov, E. I. (2013). Modelirovanie shpindel’nogo uzla obrabatyvayushhego centra [Modeling the spindle center of the machining center]. Visnik Nacional’nogo tehnichnogo universitetu «HPI». Seriya: Novi rishennja v suchasnih tehnologiyah, 11 (985), 33–38.

[16] Shevchenko, S., Mukhovaty, A., Krol, O. (2016). Geometric Aspects of Modifications of Tapered Roller Bearings. Procedia Engineering, 150, 1107–1112. doi: 10.1016/j.proeng.2016.07.221

[17] Stefanov, G., Tsankov, P., Ivanova, N. (2006). Prouchvane na tehnologichni metodi i shemi za regenerirane na otraboteni masla [Study of technological methods and schemes for regeneration of waste oils]. Osma nauchna konferenciya – “Smoljan-2006”-Sbornik dokladi, 243–247.

[18] Tsankov, P. (2015). Numerical Investigation of the Influence of Gas Temperature upon the Characteristics of Flat Aerostatic Bearing using CFD-Simulation. IJAR (Indian Journal of applied research), 5 (4), 764–766.

[19] Sokolov, V., Krol, O. (2017). Installations Criterion of Deceleration Device in Volumetric Hydraulic Drive. Procedia Engineering, 206, 936–943. doi: 10.1016/j.proeng.2017.10.575

[20] Sokolov, V., Rasskazova, Y. (2016). Automation of control processes of technological equipment with rotary hydraulic drive. Eastern-European Journal of Enterprise Technologies, 2 (2 (80)), 44–50. doi: 10.15587/1729-4061.2016.63711

[21] Reshetov, D. N. (1972). Detali i mehanizmy metallorezhushhih stankov [Details and mechanisms of metal-cutting machine tools]. Vol. 2. Moscow: Mashinostroenie, 520.