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SELECTION OF KINEMATIC STRUCTURE FOR PORTABLE MACHINE TOOL

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S u m m a r y

The article presents the problem of selecting kinematic structures for the proposed portable machine tool. Developed methodology of selection has been based on the detailed design requirements and elimination conditions formulated thanks to them. The paper describes the program developed to assist the process of selecting the kinematic structures for the portable machine tool and the results achieved.

Keywords: portable machine tools, kinematic structure, design

Dobór struktury geometryczno-ruchowej obrabiarki mobilnej

S t r e s z c z e n i e

W artykule przedstawiono problem doboru struktury geometryczno-ruchowej dla projektowanej obrabiarki mobilnej. Opracowano metodykę doboru struktury geometryczno-ruchowej w oparciu o szczegółowe wymagania projektowe i sformułowane kryteria. Zaprezentowano sposób działania opracowanego programu wspomagającego proces wyboru struktury geometryczno-ruchowej obrabiarki mobilnej oraz przedstawiono uzyskane efekty.

Słowa kluczowe: obrabiarki mobilne, struktura geometryczno-ruchowa, projektowanie

1. Introduction

Modern development trends in the field of machine tools, such as shortening the processing time while minimizing manufacturing costs prompt their manufacturers to look for new, innovative solutions. These include portable machines, also called mobile. These machine tools are well suited for processing large-size objects which often located in places not easily accessible. They may be used in construction of new facilities such as wind farms, pipelines, telecommunications masts, et c., as well as for regeneration of equipment and technical installations such as vessels parts or power plants turbines. Their

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biggest advantage is the ability to carry out on-site machining without having to dismantle and transport the facilities.

Mobile machine tools group is one of the most diverse groups of technological equipment, in terms of their structural configuration. Within this system it is possible to conventionally single out the machine tool carrier system (UNO) – including only those components involved in the process of transferring the load arising from operating the machine [1]. The UNO consists of the geometric structure, determining the spatial distribution of the constituent kinetic units the machine tool, mainly body parts and rails connecting them, as well as the kinetic structure defining the physical movements performed by these units. This structure defines a set of component motions necessary to perform the work process [1-3]. Assembly of these structures is defined as the kinematic structure (SG-R) of the machine tools, implemented as the machine tool guideway system.

When designing a machine tool SG-R selection has a significant impact on the general technical and operating characteristics, the accuracy of machining in particular. Having realised the importance of the issue, many researchers set themselves a goal of selecting the optimal SG-R machine tools [1-14]. These works usually applied one of two ways to describe the SG-R: functional [2-4] or structural [5]. Despite the development of the SG-R selection methods the associated project processes are still time-consuming, intuitive and require vast knowledge and considerable experience.

The desire to extend the machining capabilities encourages manufacturers to equip modern machine tools with CNC machine control systems with five axes. It clearly and significantly increases the number of the SG-R variants necessary to consider. New solutions to this problem are sought, e.g using graph theory [5, 14] or neural networks [8], there are attempts to develop an appropriate software supporting the choice of the optimal SG-R. The authors of this article have attempted to develop a selection method and software for 5-axis mobile machine tool SG-R.

2. The issue of kinematic structure selection

In the modern approach to machine tool designing the optimal SG-R selection is an important issue within the process of designing and engineering. This issue is given most attention at the stage of conceptual design. The scope of the present study refers to the commonly named preliminary selection of the SG-R. The study includes the selection of possible alternative solutions, at this stage it does not include activities related to the analytical prognosis of the properties of future machines.

The study has been based on the methodology of SG-R design developed by Vragov [4]. This concept present the SG-R in the form of structural code. The structure of the model include: (a workpiece – PO) → symbols corresponding to the coordinate axis directions of movement of successive UNO elements and the stationary body designation → (tool – N). The symbols of working units in the system are identified by letters of the alphabet according to the Polish Standard [15], while the stationary unit is marked 'O'. The basic SG-R model created this way must be a permutation of symbols of its components. A set of all possible permutations of the SG-R variants creates a matrix SG-R model [2-4]. Vragov proposed two-step course of action. The first step involves the formulation of selection criteria based on the requirements of the machine tool. Next, the matrix SG-R model undergoes a process of selection on the basis of the adopted selection criteria. In the second step the pre-selected SG-R set is subjected to a comparative evaluation. This methodology, however, does not prescribe specific actions for a comparative assessment and final selection [2-4].

3. Preliminary selection of kinematic structure

3.1. Definition of steps methodology

Having proceeded correspondingly with Vragov methodology, the scheme of necessary project activities has been adopted, including the following steps:

- Identification of the basic machining works and working conditions. Formulating design requirements.
- Analysis of the feasibility of design requirements. Conceptual works.
- Selection of optimal SG-R variants.
  - generating the total number of possible variants,
  - formulating the conditions of elimination,
  - selecting the options based on the terms of elimination.
- Evaluation of selected variants.

3.2. Formulating design requirements

Determining design requirements for portable machines is a complex process, due to the expected versatility and specific character of this type of machine work. Within the framework of this study, this process has been carried out in three stages. The first step set out the basic functions of the machine tools (such as positioning the tool and the workpiece with respect to each other and mounting the machine tool on the workpiece, implementation of the required working motions) [16]. The next stage included the analysis of existing design knowledge, taking into account: information from manufacturers and distributors of equipment manufactured currently. A collection of data derived from public industrial directories were analyzed during formulation of these requirements [17-22]. These actions helped to determine the general features of the existing portable machine tools. Descriptions of these features, both commercial and technical, have been summarized in Table 1.

The third step of the analysis was customer requirements and preferences, the results of the research conducted by IDI (individual depth interview) being the source of information [23]. These actions lead to the conclusion that the previous solutions do not fully meet user expectations for mobile machine tools. This step also included formulating the most important criteria for the users selection of the machine tools. These criteria have been summarized in Table 2.

Table 1. Characteristics of portable machine tools

No.	Feature	Description
1.	Universality	Low flexibility in both machining operations and the types and sizes of workpieces
2.	Machining accuracy	High dependence on operator error
3.	The repeatability of machining results	Highly operator-dependent, due to the manual process of Positioning and mounting the machine tool on the workpiece
4.	Preparation time	Time-consuming, manual process of positioning and mounting the machine tool on the workpiece
5.	Weight	Relatively large weight regarding the needs of the mobile machine tool
6.	Process automation	Low degree of automation, often hand-driven motion of feeders

Table 2. Selection criteria and expectations of mobile machine tools users

No.	Criterion	Expectations
1.	Weight	Minimizing machine weight
2.	Machine tool dimensions	Minimizing the dimensions of main components of the machine tool
3.	Workpiece dimensions	Increasing the capacity of the dimensions of the workpieces
4.	Machining difficulty	Facilitating machining work and minimizing the impact on the accuracy of the machining operator as well as machine tool ergonomics
5.	Difficulty in positioning and mounting the machine tool on the workpiece	Improving ergonomics of the machine positioning, mounting and transportation (additional supporting elements)
6.	Maintenance difficulty	Improving organization of maintenance process, typification and unification of parts
7.	Resistance to external conditions	Providing greater resistance to the influence of the machine the external conditions (atmospheric factors)
8.	Durability	Increasing the durability of machine tool machine tool life in both the treatment process and transport
9.	Efficiency	Increasing productivity, e.g. by increasing the efficiency of propulsion engine power
10.	Training systems	Improving access to training and instructional programmes
11.	Safety	Ensuring the safety by reducing the emission of noise, emergency shutdown systems and additional shielding elements

3.3. The conceptual work

Developing the overall concept of the portable machine began by identifying the type of machining tasks performed by the machine. The analysis of market needs of the industry suggests the basic use of machine tools in the area of power industry and infrastructure. Taking this into account, the workpiece type has been specified as large-size pipe flanges. Furthermore, it was assumed that the range of machining operations should include the face and the cylindrical surface of the flanges and the undercuts and screw holes on the face of the flange. This state of machining tasks suggests that the proposed machine tool should have the kinematic characteristics of the milling machine.

Given the basic characteristics of the idea of a mobile milling machine, it is possible to compile the following list of basic expectations: mounting on the workpiece, machining flat surfaces as well as cylindrical, required machining accuracy.

General design guidelines can be formulated on the basis of detailed expectations. The basic condition in terms of mobility is minimizing machine weight, as well as reducing its outer dimensions (working in difficult access conditions). Preparing machine for operation requires its mounting on the workpiece, an important problem being the direct positioning of the machine against the workpiece while minimizing the impact of these actions on the accuracy of machining. While seeking a solution to this problem the concept of automatic error correction was proposed to correct the machine position against the workpiece. Such action may include introducing pre-measured and developed values of correction to the processing programme. Implementation of this concept requires incorporating into the basic set of three feed movements, required by the milling treatment, two additional controlled movements allowing the performance of corrective movements.

Commencing conceptual work, in addition to the basic guidelines, the variety of possible solutions should also be taken into account. One way to seek diversity of solution variants is the use of inversion method based on the creation of possible structural variant through reversing roles, movements, positions, shapes or elements constituting the structure [24].

Rationality of the conceptual actions dictates, in case of the kinematics of machine design, analysis of the necessary components of shaping movements, such as morphological tree method. Illustration of the Conceptual activities carried out with regard to the mobile machine tool may be the analysis of ways to provide the necessary components of shaping movements backed by inversion method (Fig. 1).

Based on the above-mentioned techniques four conceptual variants of machine tool kinetic structure were identified (see Fig. 1). In all variants the main movement work is provided by a tool, namely the milling head, placed in a moving headstock, the options being different in terms of feed movements.

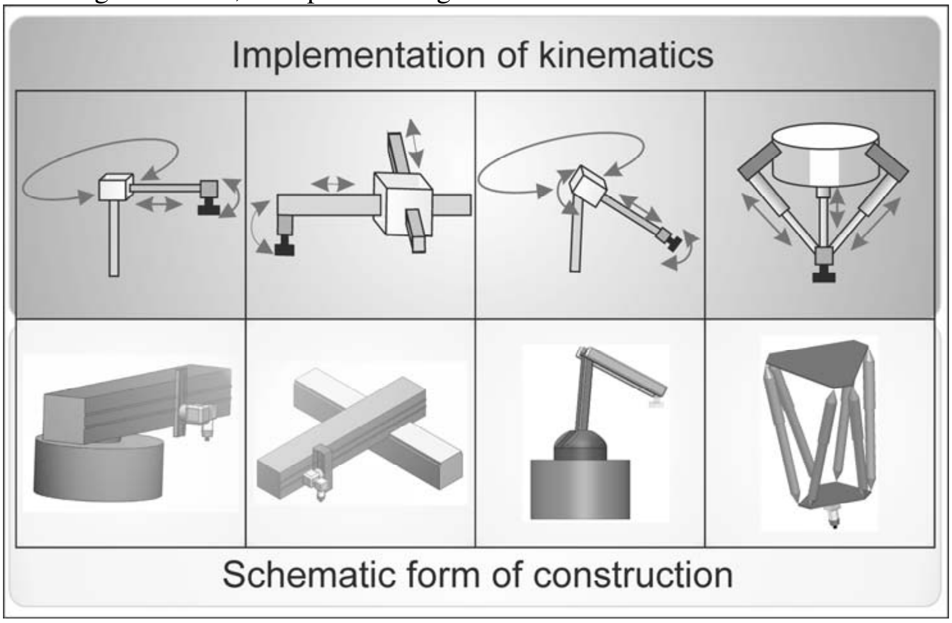

Fig. 1. Summary of possible solution concepts

In the first variant, reaching basic points lying on the surface of the workpiece, meaning the frontal flange plane, is possible by combining the rotation with the rectilinear motion. This can be implemented in the form of rotating arm with additional conversion in the vertical axis. The second option provides the necessary tool position with respect to surface finish by superpositioning two translational motions conducted along two mutually perpendicular axes, as in conventional milling. In another variant, the corresponding correlation of rotating arm swinging motion allows the tool to reach the respective points of machined surface. Articulated construction of the arm allows its necessary outreach variability. The next step in developing this concept may be multiplication in the number of self-aligning arms, creating the object pursuing the idea of so-called parallel kinematics. Under this scenario, a complex movement of the tool is a result of changes in the length of the arms connected pivotally with a fixed element.

In the case of the first and second variant elementary movements can be easily determined and assigned to mobile and fixed units by specifying the kinematic structure. As for the third and fourth variants the interaction of elementary moves is present. Difficulties may arise in defining tool position in processing space and the negative impact of the individual motor connections may be observed.

Given these arguments, and the adopted design requirements (see 3.2) it was decided to exclude the last two options from further consideration. From the point of view of the operator using the portable machines, the technical implementation may be too complex and inadequate to the expectations formulated.

3.4. Selection of optimal variants of kinematic structure

According to the adopted methodology, the search for optimal SG-R begins with formulation of the basic model. This pattern is formed on the basis of analysis of all the feed movements processing necessary for the treatment already at the conceptual stage. In the case considered, milling was adopted as the basic type of treatment. A set of three movements required by this type of treatment has been supplemented with two additional movements arising from the need to improve the accuracy (see 3.3).

The description of the basic SG-R model includes mobile and stationary units forming the kinematic chain. Formalizing a general description of the model, the following symbols have been adopted to mark its components:

X – cross-feed axis,
Y – longitudinal feed axis,
Z – axial feed axis,
A – axis of rotation with respect to axis parallel to X,
B – the axis of rotation with respect to axis parallel to Y,
C – axis of rotation with respect to axis Z,
O – fixed module.

The basic SG-R variant, can be recorded as: ABXYZO (in accordance with the formal conditions adopted). Performing permutation (without repetition) on the elements of basic design allows full array of possible options for structural design. This action can be presented in the form of the following relations:

$$T_{ws} = n! \tag{1}$$

where: T_{ws} – the array of structural design, n – number of SG-R modules under consideration.

In the presented case of five mobile modules and one stationary model, the use of equation (1) gives 720 different variants of the structural code. Analytical activities on such a vast data set are only possible with the use of appropriate software.

For the purpose of this work, a computer program assisting the process of selecting the optimal variant of the mobile machine SG-R tool has been developed and its scope of activities adapted to machines with serial kinematics.

The program was developed in MatLab environment [25, 26]. It allows exclusion of structural code variants which do not fulfil specified set of criteria. The set of these criteria has been defined based on the conclusion from the expectations analysis of mobile machine tools users. The program allows the user to adopt any number of conditions. Furthermore, the conditions have been formulated in a way ensuring the lack of interactions, which means that the order of applying various conditions does not affect the final result.

Formally, the elimination conditions take the form of the structural code of corresponding to the selection criterion. The process of elimination takes place using Boolean operations on the adopted sets of conditions and a full array of structural models.

SGR – Elimination program carries out the following actions:

- generating a full array of structural codes,
- defining a list of criteria and working conditions for elimination,
- selecting of a set of options fulfilling the adopted criteria.

SGR – Elimination scheme has been shown in Fig. 2.

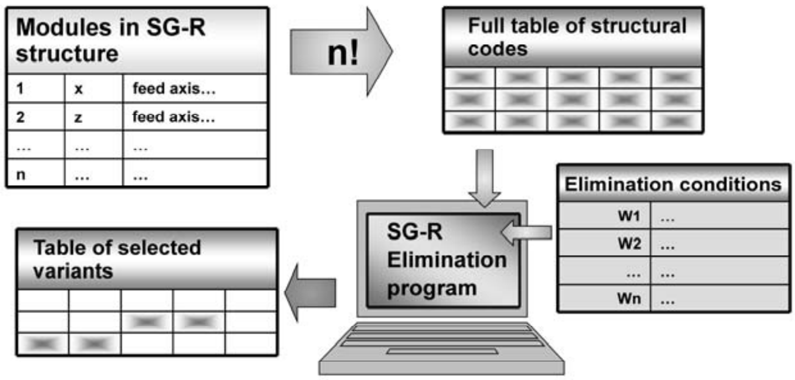

Fig. 2. SGR – Elimination program scheme

Based on analysis results included in Section 3.3 the following two basic formal patterns of SG-R implementation in the proposed mobile machine have been adopted: XYZABO and XZABCO. Appropriate set of selection criteria was developed for these models by formulating elimination conditions. The data prepared were entered into the SGR –Elimination program carrying out two calculation sessions separately for each basic model, with the following elimination conditions (Tab. 3).

Taking into consideration specific information contained in Tab. 3, particular conditions can be formulated as follows.

Weight and dimensions of the workpieces (large-size items) disqualify, for technical reasons, placing the workpiece on the machine tool. Using the inversion method proposes adopting a method reverse to conventional machines. It is assumed that the workpiece is stationary element, and therefore the symbol of this module (O) should be the beginning of the structural code. This condition has been marked as W1 and demonstratively illustrated in Fig. 3b.

Table 3. Conditions for elimination of SG-R solution variants

No	Condition	Condition details
W1	Minimizing the impact of weight the workpiece weight	Workpiece is stationary
W2	Kinematics of machining- milling	Providing the necessary feed movements. The required sequence of movements: CX, XY or YX
W3	Minimizing weight of moving parts fed vertically by chain motion (force of gravitation)	Module of the highest weight should not move vertically. Z-axis should be behind the X or Y axis
W4	Improving accuracy by adjusting the angular position of the axis of the tool against the workpiece surface.	Two additional correction axes (A and B), allowing the change of the angular position of the axis of the tool against the surface of the workpiece. axes A or B – always at the end of the structural formula due to the tool.
W5	Improving accuracy by eliminating the effect of axes other than the corrective on determining the angular position of the axis of the tool against the workpiece surface.	A direct link between axis A and B.

Providing the necessary feed movements (kinematics milling) requires a special sequence of moves. Depending on the solution, the concept can be realized by the sequence axes: XY or YX and CX. Lack of direct link axis in these sequences makes it impossible to work in the whole area of working space required. This condition (W2) has been shown in Fig. 3c.

Aiming at improving the properties of the newly designed mobile machine tool a requirement has been formulated to minimize the weight of moving machine parts fed in a vertical direction [4]. In adopting the SG-R machine, one should strive to place the highest weight modules in such a way that they do not have to move gravitation wise. As the largest weight has been assigned to modules moving in the direction of X and Y axes, they should be located before the Z-axis. W3 condition has been demonstratively shown in Fig. 3d.

Implementing the design requirements of improving machining accuracy by allowing error correction of the mobile machine positioning on the workpiece, two additional correction axes (A and B) have been introduced. Effective change in angular position of the axis of the tool respectively to the workpiece surface finish can be achieved by location of the modules performing the movements of the axes A or B at the end of the structural code. The fourth condition can be illustrated by analogy to the previous conditions (Fig. 3e).

The requirements for machining accuracy improvement necessitate actions taken in order to correct the angular position of the axis of the tool respectively to the workpiece surface. Introduction to two additional corrective axis (A and B) control and directly linking them together reduces the impact of other controlled axes on corrective action (determination of corrections). The fifth condition can be formulated as a required sequence of movements of the axis of AB or BA. W5 condition has been shown in Fig. 3.f.

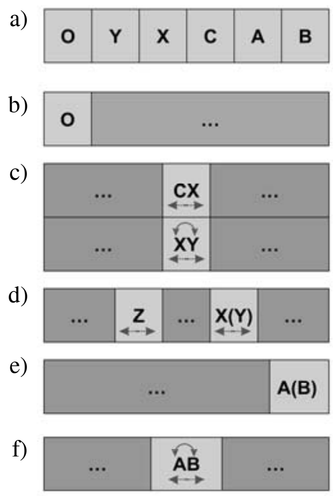

Fig. 3. Graphic demonstration of SG-R variants elimination conditions: a) a sample form of the structural code, b) W1 condition c) W2 condition, d) W3 condition, e) W4 condition, f) W5 condition

Adopted elimination conditions have been applied in SGR-Elimination and mobile machine tool SG-R variants selection have been made, which was demonstratively shown in Fig. 4.

As a result of these actions variants have been pre-selected and two equivalent structural models for both design options have been obtained. Figure 5 shows schematic examples of possible technical implementations of selected SG-R.

The basic implementation of the first variant of the concept labeled as ABCXZO. In the first structure is still O module, which is directly connected to the rotary axis of the module C. This module moves with the arm movement of the X-axis and Z axis movement of the column at the end of the chain positioned with the cutting tool spindle. Complementing the move set of modules (OCXZ) with two additional corrective movements, carried out by rotating modules (A and B), you get two full variants, i.e. OCXZAB (Fig. 4a) and. OCXZBA (Fig. 4b).

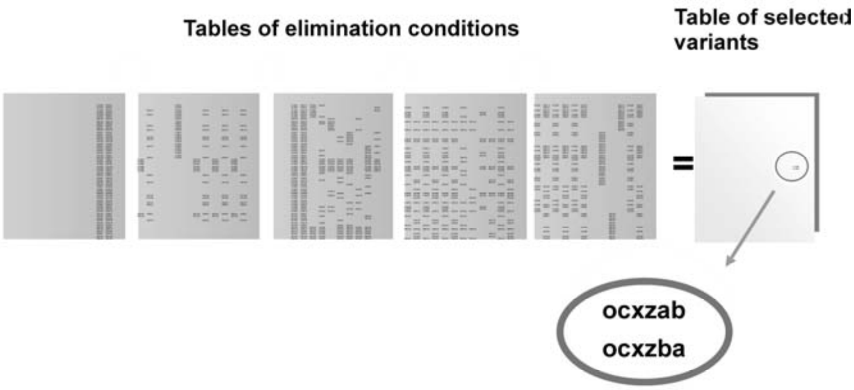

Fig. 4. Selection of SG-R solutions variants

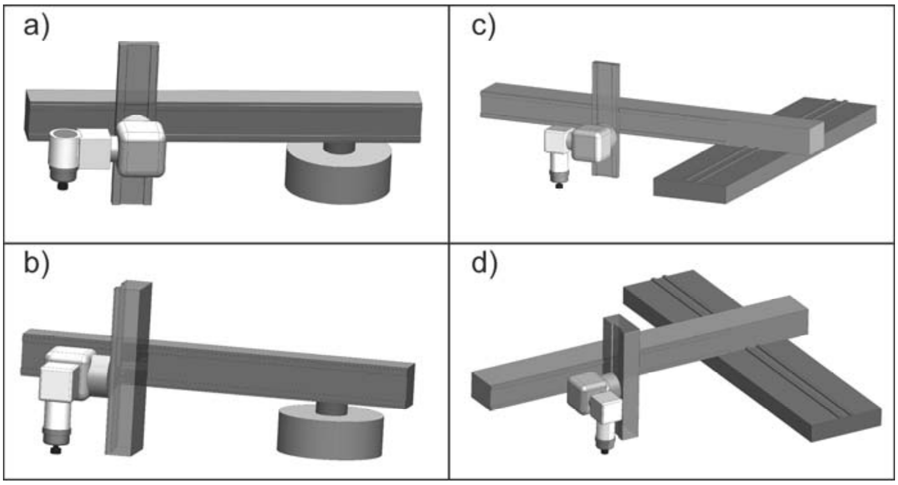

Fig. 5. Selected structural formulas: a) OCXZAB, b) OCXZBA, c) OXYZAB, d) OXYZBA

Similarly, the second of the design options identified as ABXYZO support may take the form shown in Fig. 4c (OXYZAB) and Fig. 4d (OXYZBA).

It is obvious that an alternative solution to this conceptual variant forms may include the following structural formula OYXZBA and OYXZAB. It should be noted, however, that the changes have little significance in relation to variants OXYZBA OXYZAB, what allows considering them as equivalent.

Conclusions

In conclusion, it was possible to formulate methods of selection of geometric and physical structure of the mobile machine by specifying the design requirements and the development of the elimination conditions based on these requirements. The selection procedure was based on an analysis of the functional description of the required shaping movements, carefully developing appropriate conditions for the elimination of alternatives using the information concerning the needs of future portable machine operators. Adopting a five-movement structure of the geometric means that the number of the necessary options under consideration require the use of computer techniques. Supporting such actions with the special program, significant reduction in the number of variants has become possible, defining a set which best fulfilled the adopted criteria. Despite this, the final selection of the optimal geometric and physical structure of the mobile machine requires additional steps of determining such characteristics or properties that allow to estimate individual solutions. This can be achieved by applying the appropriate method of modeling of the carrier [27] and an analysis (e.g. static properties) in order to estimate the indicators useful in the evaluation and selection of variants of geometric and physical structure of the machine.

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