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MODELING THE CARRYING SYSTEM OF THE MACHINE TOOL UNDER THE CONDITION OF VARIABLE CONFIGURATIONS OF ITS MOTION UNITS

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Summary

This paper presents the finite element method used to predict the properties of carrying systems in machine tools under the condition of variable configurations. Computational analyses used the hybrid models of the carrying system. Based on the analysis of the carrying system of a milling machine, this study analyzes and evaluates static stiffness distributions in its area of treatment.

Keywords: modeling, prediction of properties, machine tool carrying system

Modelowanie układu nośnego obrabiarki w warunkach zmiennych konfiguracji jej zespołów ruchowych

Streszczenie

W artykule omówiono zastosowanie metody elementów skończonych w procesie prognozowania właściwości układów nośnych obrabiarek w warunkach zmiennych konfiguracji. W prowadzonej analizie obliczeniowej stosowano modele hybrydowe układu nośnego. Przedstawiono analizę układu nośnego frezarki oraz opracowanie wyników obliczeń, umożliwiające zarówno ich analizę, jak i ocenę rozkładu sztywności statycznej w przestrzeni obróbki frezarki.

Słowa kluczowe: modelowanie, prognozowanie właściwości, układ nośny obrabiarki

1. Introduction

Currently, machine design is increasingly dependent on computer simulations which improve the efficiency of the design process. Predicting the properties of a newly designed structure based on computer simulations does not only shorten the design process but limits the number of produced prototypes. One of the most common methods of machine tool modeling is the finite element method [1].

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Suitable design of carrying systems is a very important element of machine tool structure [2]. Due to the nature of machine tools, the use of universal programs of the finite element method can often be inefficient. One of the major problems in modeling is a variable configuration of the carrying system units, directly associated with the specificity of the machine tool's operation. It can be assumed that the change in the relative positions of motion units affects the properties of the entire object determined at a hypothetical point of contact between the tool (cutting edge) and the surface of the workpiece. Therefore, a comprehensive prediction of these properties requires their determination at various points of contact in the area of treatment. The variability of the machine configurations is shown below on the example of a milling center (Fig. 1).

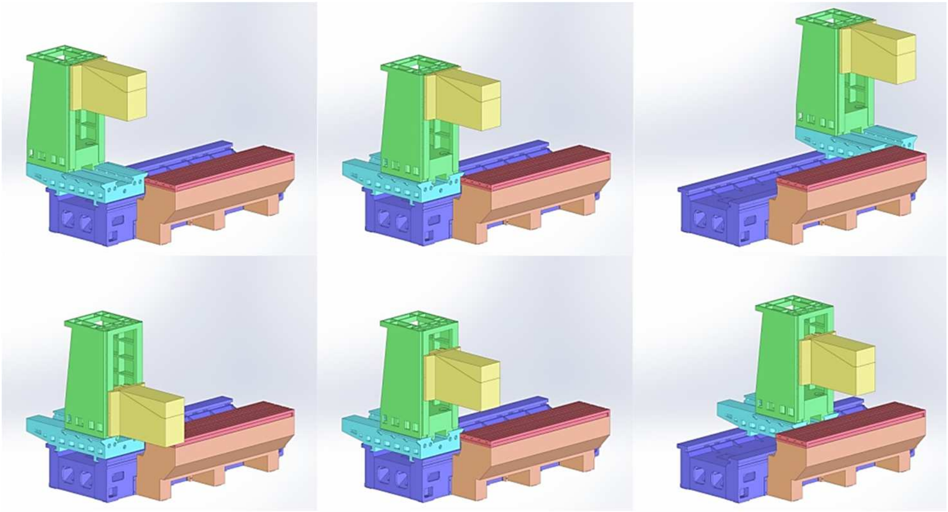

Fig. 1. Various machine tool configurations shown on the example of a milling center

In modeling carrying systems, taking into account the variation of the relative position of the individual motions units in the carrying system require a model for each configuration corresponding to the analyzed point of contact between the tool and the workpiece. In this situation, the use of classic, multidimensional FEM models is very labour-intensive and time-consuming, and therefore inefficient. In this paper, authors present a modeling method developed at the Institute of Mechanical Technology at the West Pomeranian University of Technology [3]. Dedicated to carrying systems, the method makes it possible to develop models which show much higher efficiency, while maintaining a suitable precision/ /accuracy of modeling [4]. An example of computational analysis carried out for a newly-designed three-axis milling machine is described, the computations concerned the characteristics of its static stiffness.

2. Modeling

The determination of the spatial distribution of static properties, especially in the carrying system at the point of the contact between the tool and workpiece, requires the preparation of a model for each point of this distribution. Depending on the assumed plan of research, such a simulation requires a dozen or several dozens of modeling and computational sessions. In order to simplify the procedure, hybrid versions of the carrying system model are proposed [5].

Hybrid modeling of the carrying system begins with the creation of geometric form of all components of the structure, such as body components, guideway sub-assemblies and the elements of drives responsible for traversing movements. These geometric forms are subject to geometric simplification according to the prinicples of the finite element method. At this stage, the main aim is to introduce changes in the geometric form of individual parts so that the dimensionality of the model is limited but the results of the analyses are not significantly affected. The information about the effect of such simplifications on the results of analyses may be based on the experience and knowledge from the previous research on similar structures. Quite frequently, if such information is not available, the introduction of a given simplification is based on partial analyses where a given object (usually an individual unit) is modeled in two variants: without simplifications and with simplifications. Comparison and evaluation of the results of these variants decides about the use or rejection of a given simplification.

After the creation of suitable geometric forms, they should be logically connected into functional sub-units, and then into units corresponding to the movements in individual axes of the machine tool. This process should correspond to the geometric and motion structure of the machine tool, taking into account the relative positions of the motion units and their connection with the fixed main body of the machine. This clustering into motion units is crucial for the development of the carrying system model that is meant to enable analysis in many points of the machining space. The individual motion units are assigned the initial positions corresponding to the assumed baseline configuration.

Hybrid models of the machine tool carrying systems are very useful due the separation of solid and contact structures. This makes it possible to perform the discretization of the solid structure of the motion unit in a machine tool independently of guide connections (that belong to the contact structure in the model). When the solid structure is combined with the contact structure, one may introduce changes in the location of individual motion units relative to one another, combining them in a model via the elements of the contact structure. This method of creating an entire model of the carrying system makes it possible to introduce variations that correspond to changes in the configurations of the relative locations of the motion units. The assumed concept of modeling decreases labor intensity and shortens the time necessary for the development of the model. The model of solid structure is developed only once for the initial configuration, and then appropriate procedures are used to displace discretized motion units to reach a given point of contact between the tool and workpiece. This approach for creating a model of the carrying system is presented in Fig. 2.

Combining the solid and contact structures in a specific variant of configuration takes place automatically with the use of procedures based on the analysis of geometric and kinematic relations in the carrying system.

The proposed approach to modeling of carrying systems, taking into account the variable configurations of its body units, was developed for numerical procedures. The procedures were programmed and integrated with the Helicon software [5, 6] which performs calculations for the hybrid models of carrying systems.

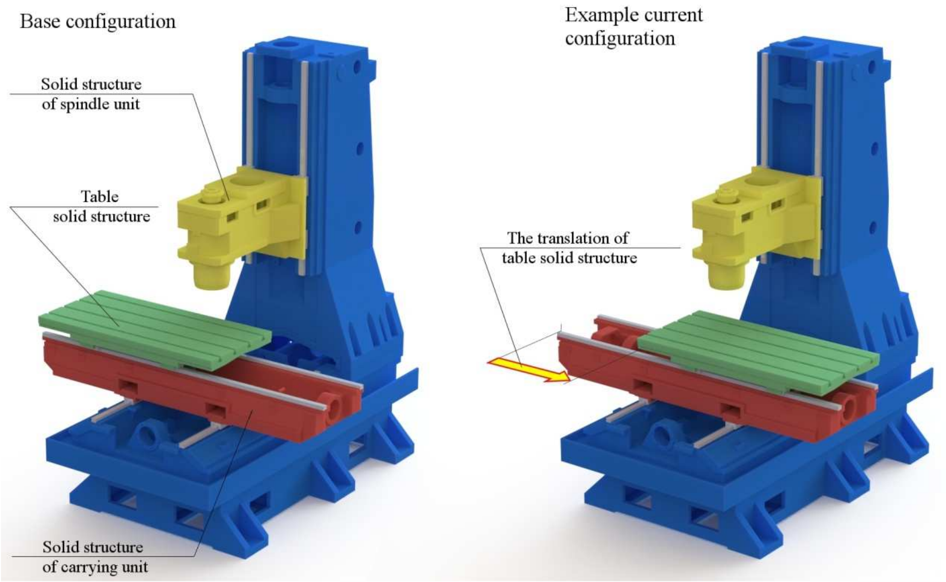

Fig. 2. The concept of developing carrying system models, corresponding to the points of contact between the tool and workpiece

3. Example of calculations

Analysis related to the carrying system of a three axis milling machine, presented in Fig. 3.

The geometric and mobile structure of the machine tool consists of the cross table which can move in X and Y axes, and the spindle that may move in the Z axis. The guideway system of the milling machine was based on the THK roller guides [7]; SNR25R units were used in the horizontal guideways (X and Y axes) while SNR25LR units (elongated version) were used in the vertical guideway (Z axis). In the milling machine, CNC was used for all axes, and the possible movements in the following directions: longitudinal (X) 760 mm, lateral (Y) 440 mm and the vertical (Z) 510 mm.

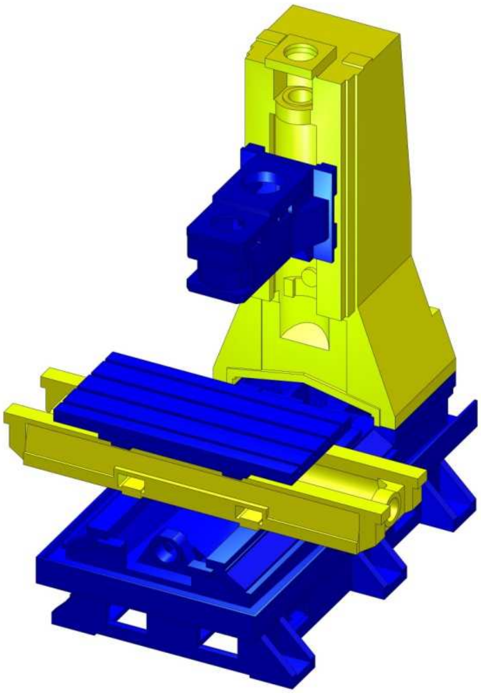

Fig. 3. The carrying system of the analyzed milling machine

Modeling began with establishing the object's geometry, with the use of the SolidWorks design-supporting software [8]. Body elements and the elements of roller sub-units (bodies of carriages and rails) were developed in the form of three-dimensional parts (blocks). Those parts were combined in locations corresponding to the motion units of the machine tool. In order to limit the excessive dimensionality of the model, the geometric form of those parts were subject to simplifications consisting in omitting small holes, rounded fragments and surface faults. The next stage of hybrid modeling was the separation of the solid and contact structures.

The solid structure included the solid body frame elements, while the contact structure included only roller elements [5]. The solid structure also included some elements of the guideway system, i.e. bodies of carriages and rails. Structural elements responsible for traversing movements (ballscrew mechanisms) were included in the contact structure [5, 6]. The next stage of the modeling process was to distinguish the deformable and rigid substructures within the solid structure. Given the number of planned computation sessions and the complexity of geometric and structural elements of the carrying system, the following simplifying assumption was made: deformability of large body elements made as iron castings is many times lower than that of the elements of the guideway system.

This view was confirmed by a series of calculation sessions made in the SolidWorks Simulation software [8]. Individual elements of the body were modeled as deformable: table, slide, headstock, stand and bed. The serial nature of the carrying system of the considered milling center and the expected low impact of nonlinearities related to the contact structure allow to perform this type of analysis with the separation of individual solid bodies. Deformation of each solid body was studied under static loads, maintaining suitable conditions for both load and anchors. For example, the table was loaded with external force and anchored in the places of the guideway system's influence. On the basis of this model, table deformations were determined and the resulting reaction forces in anchors were used as the load for slide.

The same method was used to analyze the deformations of all solid bodies in the carrying system and determine the displacements in the selected checkpoints. The analysis also allowed the evaluation of the displacements. The obtained results did not exceed 2.5 µm in the most extreme cases (for the assumed loads), which in our opinion confirms that it is possible to omit the deformations of solid bodies in the main body of the machine tool in further analyses. Due to the very comprehensive description of analyses of solid body deformations and their standard nature (and thus typical engineering calculations) this study presented only examples of results.

Figure 4 presents the distribution of displacements of the table loaded with forces parallel to its work surface, with the shown displacement of the control point. Figure 5 presents the distribution of displacements in the table loaded with forces perpendicular to its work surface.

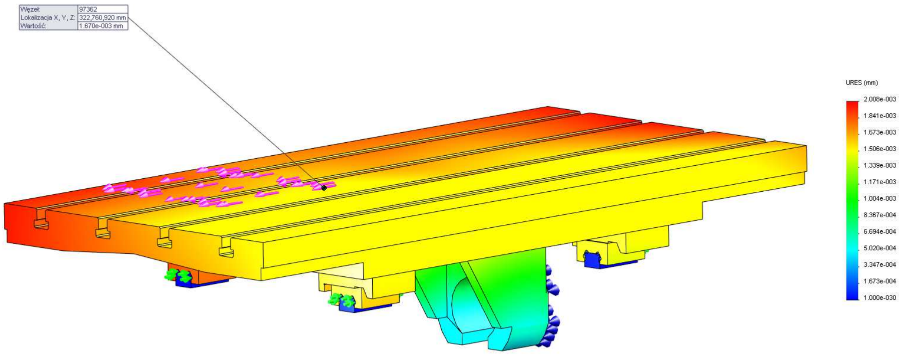

Fig. 4. The distribution of displacement of the table loaded with forces parallel to its work surface

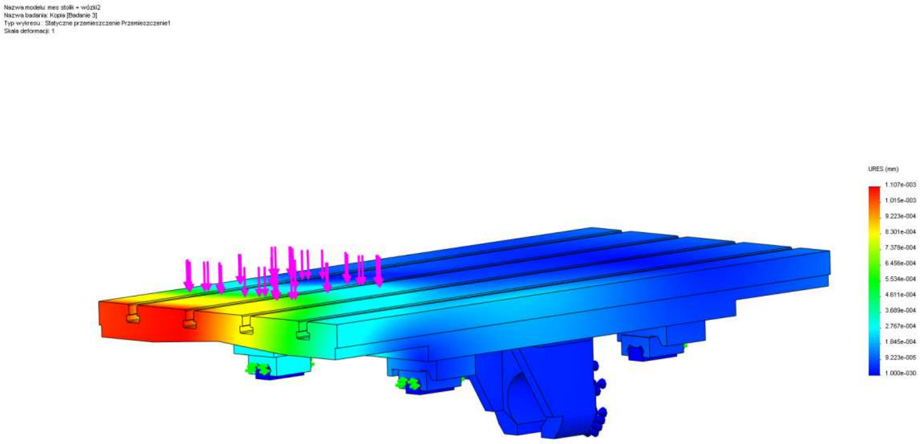

Fig. 5. The distribution of displacements in the table loaded with forces perpendicular to its work surface

According to the aforementioned considerations, it is assumed that deformable substructure consists of only the bodies of rolling subunits, whose locations in the carrying system structure are presented in Fig. 6. Individual body elements of the carrying system motion units were deemed non-deformable.

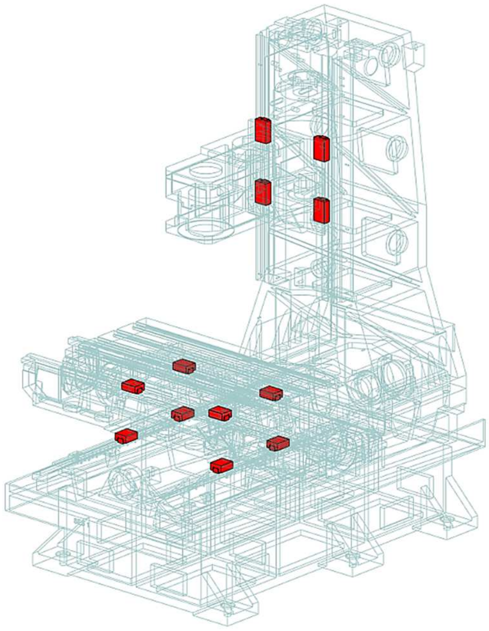

Fig. 6. The solid structure of the analyzed carrying system, with the distinguished deformable substructure

Omitting the deformability of the machine body elements resulted in a model, where only the ‘active fragments’ of guide rails were treated as deformable. The ‘active fragments’ meant those where the rail was in contact with the carriage (via rolling elements – balls). The remaining fragments of a guide rail (attached to the body elements) were treated as perfectly stiff. Figure 7 presents the adopted method of discretization for the carriage-rail pair as the elements of a deformable substructure.

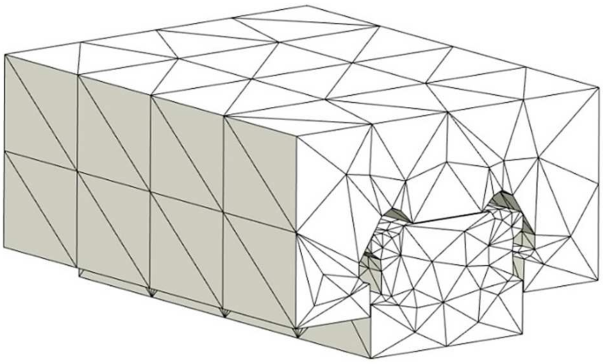

Fig. 7. Discretization of the carriage-rail

Taking into account of closure of the load circuit in the carrying system, this model also takes into account the susceptibility of the machine tool spindle. Assuming that this unit is not a particular object of considerations in the context of this analysis, it was modeled in a simplified manner. The complex susceptibility of individual components of the spindle and its bearing was clustered in the form of three translational-rotational spring elements.

The contact structure of the model consists of unilateral spring elements, replacing in the model the rolling segment, i.e. thread-ball-thread occurring in carriages and two-side spring elements for modeling feed drive mechanisms [5, 6]. The physical parameters that describe the characteristics of the rolling segments were selected on the basis of the Hertz theory. Parameters describing the characteristics of the elements modeling the properties of ballscrew mechanisms were selected directly from the manufacturer's materials.

Finally, the adopted hybrid model for the analysis of the carrying system of the milling machine included the deformable substructure consisting of 13532 nodes connected into 48254 elements and stiff substructure consisting of 5 elements. The set of information about the block structure was supplemented with the areas of cooperation between the deformable and stiff substructures. In the described model we combined the mounting surfaces of carriages and guide rails with the mainly body elements in 1492 nodes. In the contact structure we used 784 elastic elements (one side action) and three elastic elements with bilateral action modeling the traversing movements, and six elements modeling the elasticity of the spindle components.

After developing a hybrid model of the carrying system in the initial configuration, it was necessary to enter its parameterization associated with changes in the positions of individual motion units. The adopted parameters were the distances determining the position of a given motion unit relative to the guide. The different variants of the model were generated automatically by changing the parameters of the distance for each machine axis so as to set the configuration of motion units corresponding a given point of contact between the tool and the workpiece. Changes in the configuration of motion units result in change the coordinates of nodes both for the solid and contact structures. In addition, they also change the position of gravity and external loads (simulated cutting force).

This method of modifying the model, adopted in order to develop its variants depending on the configuration of motion units ensures that the solid structure remains in an unchanged form, which in turn reduces the effort associated with the preparation of computational analyses.

4. Research plan

In the adopted research plan, 15 contact points between the tool and the workpiece were established, for each of the four planes parallel to the working plane of the machine table. A total of 60 (15x4) points were examined. Those points were distributed uniformly over each of the four planes, as shown in Fig. 8. The following principle for the model determination was adopted – the contact point lying on the plane x1 and at the same time on y1 and x1 planes was labeled as x1y2z3.

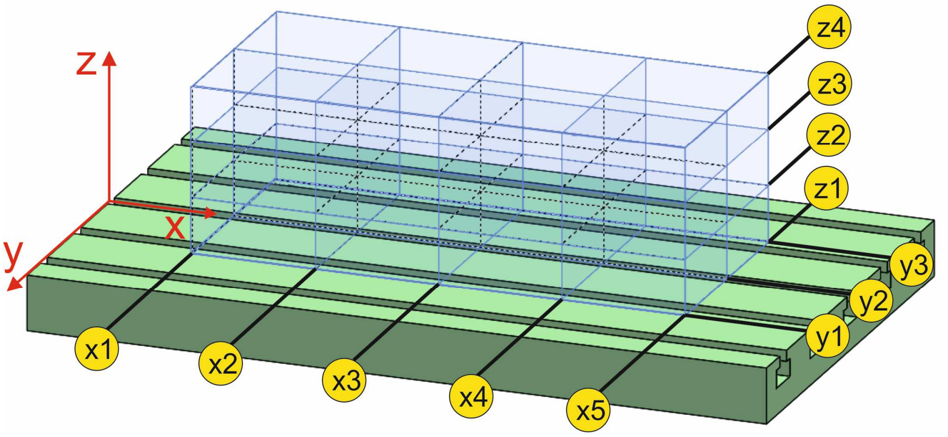

Fig. 8. The diagram of the distribution of contact points between the tool and the workpiece, corresponding to the adopted plan of analysis

The following load conditions were assumed: the system was loaded with an active force applied to the arbitrary point of contact between the tool and the workpiece, and also gravitational forces of individual motion units of the machine tool. In each configuration, changes occurred in the contact point between the tool and the workpiece and the location of gravitational forces. Moreover, it was planned that two variants of load would be considered; in the first one the active force was directed parallel to the X axis, and in the second variant parallel to the Y axis of the machine table. The variation of those forces was assumed to a range of –2000 ÷ +2000 N for each direction. That range was divided into 40 levels of force. Finally, the implementation of the adopted plan of calculations required 120 calculation sessions, with 40 solutions of the model in each session.

5. Results of calculations

The results of the conducted analyses were processed so that they could be related to the location of points in the workspace. This organization of results can be interpreted as the distribution of the stiffness coefficient in the workspace. For developing the results for individual points of contact between the tool and the workpiece, linear variation in the entire range of a given force was adopted. This made it possible to determine the stiffness of the machine tool (in the workspace) with the use of one stiffness coefficient for each measurement point. The stiffness coefficient was calculated as a quotient of force and displacement. The displacement, as the result of the spatial relative movement of the workpiece and tool was projected onto the direction of the force which induced the displacement.

The results obtained in the presented analysis constitute a comprehensive set of data, and hence this paper presents only selected data. Figure 9 show the distribution of the stiffness coefficient in the workspace of the carrying system in a milling machine for the plane z1 and the direction of applied force parallel to the X axis of the machine tool, while Fig. 10 for the plane z3 and the direction of force parallel to the Y axis of the machine tool.

The presented results indicate a few things. The distribution of the stiffness coefficient in the working space of the milling machine was uniform for the considered directions of force (X and Y). The values of this coefficient varied for both these directions. The system showed a distinctly higher stiffness for the Y direction and for X (Fig. 9 and 10). Given the information provided by the manufacturers of the machine tools and our experience, it may be postulated that despite the uneven distribution of the stiffness coefficient in the workspace (i.e. a crucial difference between the directions X and Y), the minimum stiffness coefficient (about 8 N/µm) was at a relatively good level compared to other available machine tools.

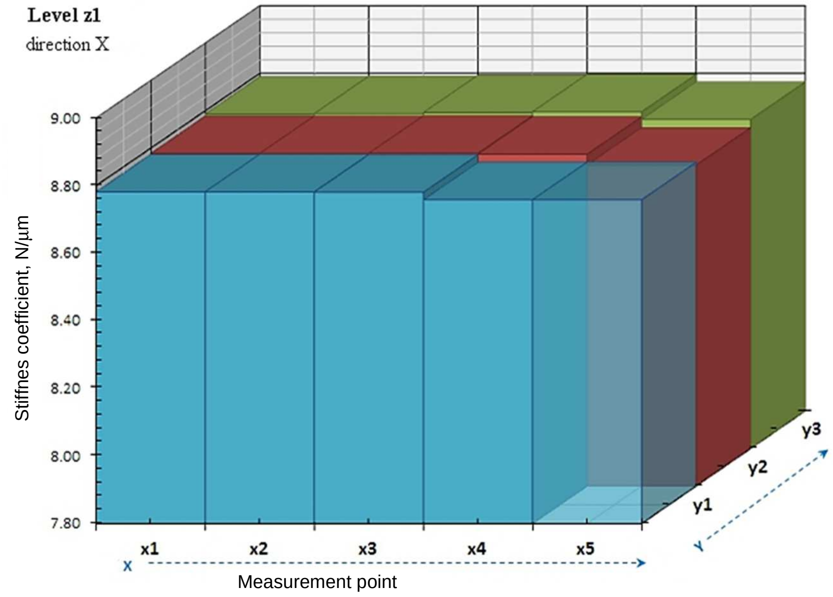

Fig. 9. The distribution of the stiffness coefficient for the workspace of the carrying system of the milling machine for the plane z1 and direction of force parallel to the X axis of the machine tool

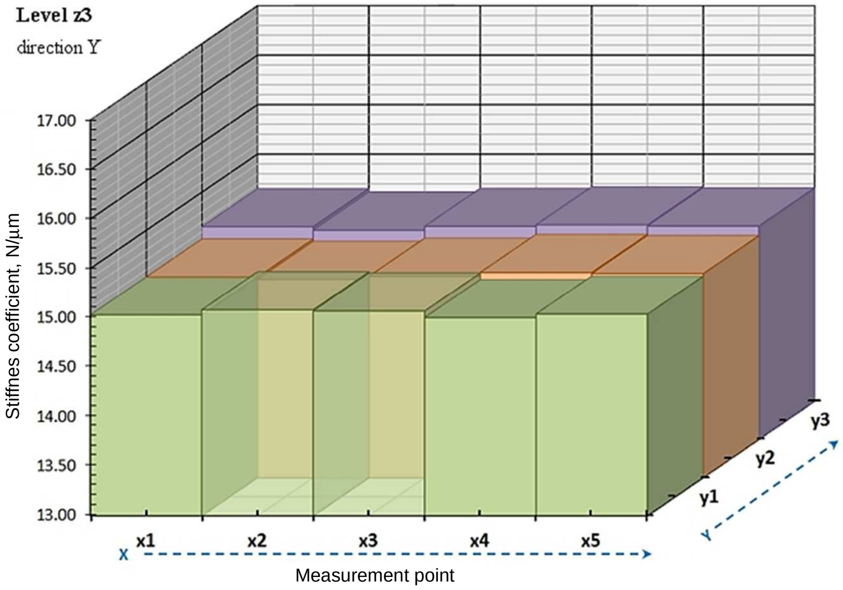

Fig. 10. The distribution of the stiffness coefficient for the workspace of the carrying system of the milling machine for the plane z3 and direction of force parallel to the Y axis of the machine tool

6. Conclusions

The obtained results of analyses lead to conclusions that enable a comprehensive evaluation of the tested carrying system of a milling machine, i.e. in its entire workspace. It is most useful to prepare models with a relatively low dimensionality (e.g. hybrid models), due to the significant number of calculation sessions which require a lot of effort and time.

Knowing the distribution of the stiffness coefficient in the workspace of the machine tool makes it possible to establish the areas of higher stiffness and locate precise machining there. In designing the carrying system of the machine tool, this knowledge may help introduce structural changes that would improve the homogeneity of the stiffness coefficient distribution. It is most desirable to ensure the uniformity of the resultant coefficient in the entire working space, and – in addition – improve the stiffness coefficients in the individual axes of the system, in accordance with the recommended roundness distribution.

The conclusion is that the possibility of establishing structural indicators and relating their levels to crucial points of the workspace in the machine tool allows to predict the behaviour of the object in the entire area of treatment, which undoubtedly increases the quality of decisions when designing the machine tool.

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