Annals of Emerging Technologies in Computing (AETiC)
Vol. 3, No. 4, 2019

Research Article

A Method of Body Parts Force Displacements Calculation of Metal-Cutting Machine Tools Using CAD and CAE Technologies

Taras Chetverzhuk, Oleg Zabolotnyi*, Viktor Sychuk, Roman Polinkevych and Anatolii Tkachuk

Lutsk National Technical University, 75, Lvivska str., Lusk, 43018, Ukraine
eti_tar@ukr.net; volynasi@gmail.com; svamator@gmail.com; r.polinkevych@lntu.edu.ua; a.tkachuk@lntu.edu.ua
*Correspondence: volynasi@gmail.com

Received: 24th August 2019; Accepted: 15th September 2019; Published: 1st October 2019

Abstract: This paper describes a developed new method of body parts force displacements calculation of metal-cutting machine tools using combination of CAD and CAE technologies. It was carried out the analysis of analytical methods and the method of finite elements of body parts force displacements calculation of metal-cutting machine tools. On the basis of it the requirements to the method of calculation of compound errors of processing and deviations of the form of the processed surfaces due to deformations of the body parts of metal-cutting machines are established. The method of designing metal-cutting machines is grounded, which is based on mathematical modeling of different processes. It gives an opportunity to evaluate the accuracy of the machine and the impact on it of the individual assembly already in the initial stages of designing. The calculation methodology was implemented using ANSYS finite element analysis. This technique was used in the calculations on the example of high-precision lathes.

Keywords: ***Structural Elements; Spindle; Calculation Scheme; Load; Rigidity; Finite Element Method; Deformation***

---

1. Introduction

Modern machine-building industry set to machine-tool building a task to increase the accuracy and efficiency of metal-cutting machine tools, as well as requirements for minimizing their cost. This leads to the need to search for new and improving existing machine tools designs, to the need to use scientifically based design method based on mathematical modelling of various processes occurring in the machine, which provide an opportunity to evaluate the accuracy of the machine and the impact on it of individual assembly already at the initial stages of design. Application of such

Taras Chetverzhuk, Oleg Zabolotnyi, Viktor Sychuk, Roman Polinkevych and Anatolii Tkachuk, "A Method of Body Parts Force Displacements Calculation of Metal-Cutting Machine Tools Using CAD and CAE Technologies", *Annals of Emerging Technologies in Computing (AETiC)*, Print ISSN: 2516-0281, Online ISSN: 2516-029X, pp. 37-47, Vol. 3, No. 4, 1st October 2019, Published by International Association of Educators and Researchers (IAER), DOI: 10.33166/AETiC.2019.04.004, Available: http://aetic.theiaer.org/archive/v3/v3n4/p4.html.

methods accelerates the process of project development, provides the possibility of optimizing the design and leads to a significant reduction in the cost of creating and refining prototypes.

One of the perspective directions for the implementation of scientifically grounded design method is the design of body parts of metal-cutting machine tools. Nowadays, during designing of body parts of metal-cutting machine tools mainly used calculation schemes [1] in which the real designs of metal-cutting machine tools are presented in the form of simple beam and plate models, as well as general empirical recommendations obtained on the basis of experimental studies of existing body parts. Such kind of approach does not allow to sufficiently substantiate the feasibility of the application of a particular body component design and significantly complicates the assessment of new structures of body parts, in which there is no experimental data. At the same time, recently the considerable development of methods of calculating the accuracy of machines, as well as mathematical modelling of stressed-deformed state, modelling the flow of fluid in different assemblies of the metal-cutting machine [2], especially the finite element method, makes it possible to develop and introduce new, more precise and efficient methods of calculation and optimization of machine tools' body parts.

Thus, researches aimed at developing scientifically based methods for calculating and designing the metal-cutting machine tools' body parts is an urgent scientific task.

2. Literature Review

The supporting system of the metal-cutting machine tool must provide precise reciprocal movement of the tool and workpiece. The quality of supporting system is characterized by relative displacements of its elements, brought to the cutting zone, which arise under the influence of perturbations of various situations on the machine. Body parts are part of the machine's supporting system. They provide a given location relative to each other individual assembly of the machine [3].

The main methods of calculating the body parts currently used in the design of metal-cutting machine tools are given in works [4, 5, 6]. The main task of calculating the body parts of metal-cutting machine tools is to evaluate the impact on the accuracy of the processing of their displacements that arise under the influence of disturbing loads of different nature. This effect is numerically characterized by relative displacements of the tool and the workpiece along the normal line to the surface caused by deformations of body parts.

Nowadays, analytical methods and the method of finite elements are used to calculate deformations of metal-cutting machine tools' body parts.

When using analytical methods [7, 8] the design that is calculated is presented as a set of beams or plates. By implementing certain assumptions, for each of these elements you can obtain a solution by analytical methods. In order to clarify the analytical solution coefficients obtained empirically are implemented into the calculation scheme. These coefficients are used, for example, to determine the values of bending, displacement and twisting stiffness of the beams included in the calculation scheme.

The advantage of analytical methods is their relative simplicity, and the fact that the used analytical formulas clearly show the effect of a particular design parameter calculated on its displacement, the ability to quick comparison of different design versions.

At the same time, analytical methods have significant drawbacks. When using them, we can't take into account the real geometric shape of the body parts, local deformations of the individual structural elements. Analytic solutions for complex form parts have a significant error and require correction using empirical coefficients. They, in turn, can be applied only to a limited set of constructs similar to those for which experimental data are available.

These disadvantages significantly limit the possibility of using analytical methods and lead to the need to use the finite element method. This method is described in [9].

When using the finite element method, the design that is calculated is represented as a set of simple geometric objects - finite elements. For each of them the type of the functional dependence of the distribution of displacements in this element is determined from displacements in its nodes.

Nodes provide the connection between elements, and their movement determines the stress-deformed state of the design.

The disadvantage of this approach is that the classical calculation scheme [9] does not take into account the mutual deformations of joints and connecting parts. This reduces the accuracy of the calculation and makes it impossible to use this calculation scheme to assess the impact of the form of structural elements.

All of the foregoing limits the application of the two above-mentioned approaches to the calculation of contact displacements. This leadsto the necessity to construct an approach in which their own deformations of body parts and contact deformations in joints are considered together with the actual dependence between displacements and pressures at each junction point.

The mentioned drawbacks of the used methods of calculation lead to the need to clarify the finite-elements calculations of metal-cutting machine tools' body parts in order to more attentively taking into account the deformations of the individual structural elements of the body parts. In this case, conditions of their fixing and loading (including taking into account their own displacements of parts and contact displacements in joints) should be taken into account, as well as the impact of deformations of body parts on the accuracy of the machine.

As shown above, existing methods of calculating metal-cutting machine tools' body parts do not fully ensure the consideration of their individual design features. These individual features do not allow on the stage of design sufficient accuracy an estimation of the impact of force displacements on the accuracy of the machine tool. Due to this, there is a need to develop a calculation methodology that would be deprived of these drawbacs.

3. Researches Methodology

3.1. Requirements to the method of calculating force displacements

Based on the analysis of existing methods for calculating of metal-cutting machine tools' body parts and the requirements for their design, presented above, we can formulate following requirements to the methodology for calculating force displacements:

1. Ensure the consideration of local deformations of all structural elements that have a significant effect on the displacement of the base surfaces (the boundaries of guides, the surface of the spindle towers).
2. Provide close to the actual design fastening and loading schemes.
3. During calculating a design, consisting of several parts, take into account the actual conditions of contact between them.
4. Perform calculation for any possible variant of moving assemblies location and cutting areas, as well as automatically execute a series of calculations for a given set of such variants.
5. Use a geometric design model that is calculated in an existing automated design system.
6. Calculate the stress-deformed state with the help of existing programs of finite-element analysis.

The general scheme of the proposed calculation method is presented in Figure 1.

The input data for the calculation is the geometric form of the considered body parts, forces and conditions of fastening applied to them, as well as the location of the cutting area and moving assemblies of the machine tool.

Results of the calculation are components of the processing errors caused by the deformations of considered body parts, or (in case where several variants of the location of moving assemblies are considered) deviations of the shape of the workpiece due to the deformations of the considered body parts.

During calculation, designing of the geometric and finite-element of the construction is performed, which is calculated, the application of conditions of fastening and forces, calculation of the stress-deformed state, and then we determine the displacement of the base points (on the surfaces of the body parts on which the moving knots are based), and then determine the spatial position of the moving assemblies of the machine and calculate the displacement of the tool and the workpiece, due to the cutting zone. Based on the above displacements, the components of the dimensional processing errors are calculated for a given location of the moving assemblies and the cutting zone.

Deviations of the shape of the processed workpiece are determined by calculating the processing components for different coordinates of the moving assemblies and their reduction to the coordinate system associated with the workpiece.

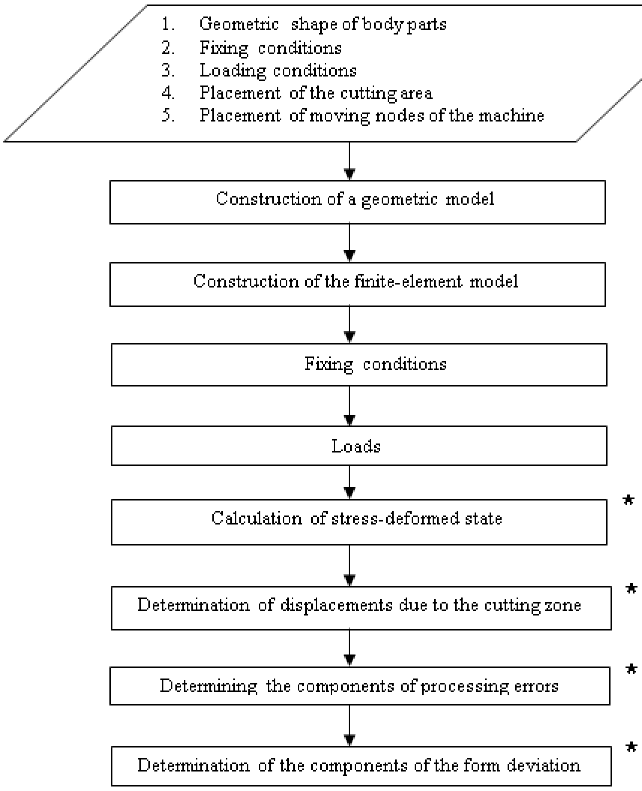

Figure 1. Block-scheme of the methodology for calculating the components of the processing errors and deviations of the shape of the processed surfaces caused by deformations of metal-cutting machine tools' body parts; * – operations that are implemented using macros

The calculation method is implemented using ANSYS finite-element analysis software [10]. For the performance of operations not specific to the metal-cutting tools' body parts, the built-in ANSYS tools are used.

Operations that are common only for the calculations of metal-cutting tools (defining forces for different positions of moving assemblies, determining the displacements of base points, the spatial position of moving assemblies, calculating the components of processing errors and deviations of the shape of the workpieces) are absent in common systems of finite-element analysis (including ANSYS). These operations were implemented using developed by user programs (macroses) written with the help of language APDL - embedded programming language in ANSYS.

3.2. Features of geometric and finite-element models used in the calculation scheme

The initial stage in the finite-element calculation of metal-cutting machine tools' body parts is the construction of a geometric and finite-element model design, which is calculated. The geometric model is needed to determine the geometric shape of the calculated structure, and the finite-element - contains complete information about the location of assemblies and finite elements, as well as the links between individual assemblies and elements.

Also, it is possible to carry out a finite-element calculation without using a geometric model, but in this case, when calculating, it is necessary to manually specify the coordinates of all nodes and build finite elements and finite element model, which is practically impossible for the metal-cutting machine tools' body parts paying attention to the complexity of their geometric shapes [11].

With the use of a geometric model, this drawback is absent because of the fact that in modern finite-element analysis software it is possible to obtain the finite-element splitting of a component automatically, which is calculated based on its geometric model. This allows us to recommend this approach for modelling metal-cutting machine tools' body parts.

Deformations of body parts can be modelled using the following types of finite element models:

– from beam and rod elements;
– from plate elements;
– from volumetric elements.

For each of these variants, the type of geometric model must correspond to the type of model of finite elements, that is, for a finite element model from beam or rod elements, the geometric model should consist of lines, for plate elements - from surfaces, for volumetric elements - from volumetric bodies.

In this article, the finite element models from the beam and rod elements are not considered, since they do not ensure the conformity of the geometric shape of the model and the real design. Models of plate elements are also not better due to their disadvantages, indicated in section 2.

Analysing above mentioned, for the calculation of metal-cutting machine tools' body parts, finite-element models of volumetric elements should be used. They have the following advantages compared with models of plate elements:

1. Provide more accurate impact of the geometry of the body part. It is possible to take into account many elements of the design that are not available for plate models.
2. In modern CAD systems, volumetric geometry models are main means of de-scribing the design of the parts being developed and used as a basis for creating of design documentation. In this situation, the surface model design, which is calculated, requires that it must be rebuilt from scratch, and the volumetric can be obtained by modifying the above design model, which provides significantly less time and reduces the probability of errors.
3. In surface models, it is necessary to set and control parameters of the finite elements (thickness) for each surface. In volumetric models, there is no such kind of a need.

The main disadvantage of volumetric finite-element models is that they usually re-quire a greater number of levels of freedom than surface one and, consequently, high costs of computing resources. However, with the development of computer technology, this problem is becoming less significant.

4. Results

In Figure 2 and Figure 3 examples of volumetric geometric and finite-element models used in calculations of high-precision lathe machines are presented.

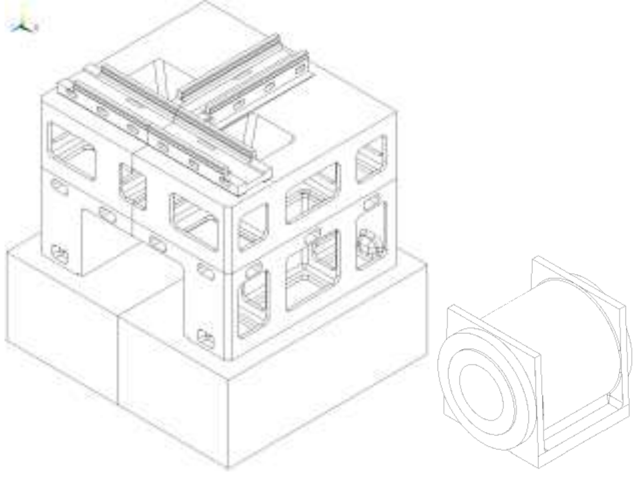

Figure 2. Geometric models of supporting system and the body ofspindle assembly of lathe machine MK6510F4

On the basis of calculations of metal-cutting machine tools' body parts, the following recommendations can be made in relation to their geometric and finite-element models:

1. From the geometric model, all structural elements that have no significant effect on structural deformation (small openings, depressions, etc.) should be excluded. This requirement is needed, basically, to provide a more qualitative finite-element partition.

2. Despite the presence in many CAE-systems of its own geometric pre-processors, geometric models should be built in CAD systems, and then exported to the CAE-system through translators. It is desirable to build them by simplifying already existing design models. This approach provides better quality and lesser time for the preparation of geometric models.

3. Areas of a geometric model, on which forces or conditions of fastening will be applied, should be allocated on separate surfaces.

4. For a finite-element model, a grid of tetrahedral elements of the second order (with additional nodes at the middle of the sides) should be used. The advantage of tetrahedral elements in front of elements with another topology lies in the fact that their use ensures the possibility of automatically breaking the geometric model into the finite elements. Currently existing algorithms for partitioning on hexahedral elements do not provide the possibility of such a breakdown automation for volumes of complex shape.

5. To estimate the calculation error associated with the size of the finite element, it is necessary to calculate several times for different variants of the finite elemental grids, which differ in size from the finite elements. In this case, the size of the finite elements for different parts of the model should be reduced proportionally to each other.

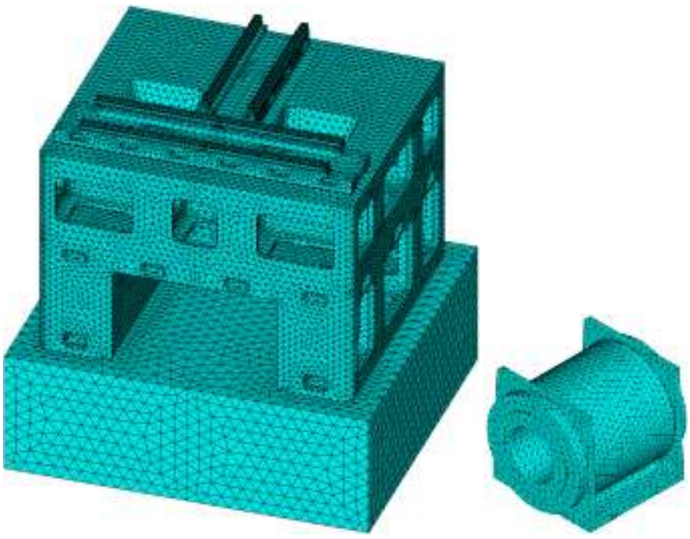

Figure 3. Models of the finite-elements of the supporting system and the body ofspindle assembly of lathe machine MK6510F4

The main task of calculating of metal-cutting machines body parts is to evaluate the effect of their deformations on the accuracy of the machine, which is characterized by relative displacements of the tool and the workpiece. In the case where the tool and the workpiece are not included in the design, it is necessary to ensure that its force displacements are brought to these elements.

During designing of the calculation scheme as the basic design is used assembly unit, including simplified models of the frame and a base of the metal-cutting ma-chine MK6510F4. Simplification of the model was performed in order to reduce the dimension of the finite element model.

In this work, first of all, we consider the features of force displacements, which are common to finite element calculations and, in particular, we reviewed types of ma-chines (Figure 4). The lathes of this design have two supports - transverse and longitudinal.

The two main cases of displacements to the cutting zone, common to this type of machines, are considered:

1. Adjustment of displacements of the body of the spindle headstock.

2. Adjustment of guides displacements.

When finding displacements of the spindle headstock, it is necessary, based on its stress-deforming state, to calculate the displacements to the cutting zone, as well as components of processing errors caused by deformations of the body of the spindle headstock. The sequence of actions during calculation of the components of the error of processing caused by deformations of the body of the spindle head includes the following steps:

1. Determination of displacements of base points;
2. Calculation of displacements of spindle supports;
3. Bringing to the cutting zone displacements of the spindle caused by deformations of the body of the spindle headstock;
4. Calculation of components of errors of treatment of diametrical and longitudinal dimensions caused by deformations of the body of the spindle headstock.

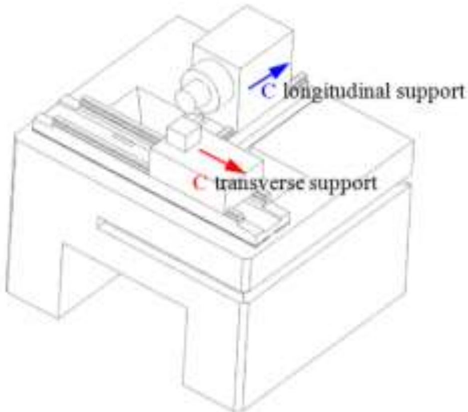

Figure 4. The location of the main components for this layout of the lathe with two supports

The base points for determining the displacement of the spindle support are a set of points evenly distributed over the surface under the spindle support (Figure 5). The displacement of each of the spindle supports is defined as the arithmetic mean of the reference points on the surface below that support. The displacement of the base points can be obtained, in turn, from the stress-strain state obtained in the finite element calculation.

The offset in the X, Y and Z coordinates of the front spindle support:

$$\Delta X_{\mathrm{A1}} = \frac{\Delta X_{\mathrm{A1}} + \Delta X_{\mathrm{A2}} + \cdots + \Delta X_{\mathrm{A}n}}{n};$$

$$\Delta Y_{\mathrm{A1}} = \frac{\Delta Y_{\mathrm{A1}} + \Delta Y_{\mathrm{A2}} + \cdots + \Delta Y_{\mathrm{A}n}}{n}; \qquad (1)$$

$$\Delta Z_{\mathrm{A1}} = \frac{\Delta Z_{\mathrm{A1}} + \Delta Z_{\mathrm{A2}} + \cdots + \Delta Z_{\mathrm{A}n}}{n}.$$

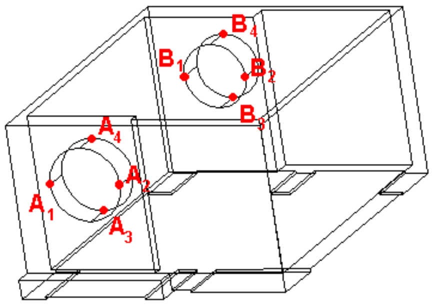

Figure 5. Points used as a base points to calculate displacements of spindle supports

The offset in the X, Y and Z coordinates of the rear spindle support:

$$\Delta X_{B1} = \frac{\Delta X_{\mathrm{B}1} + \Delta X_{\mathrm{B}2} + \cdots + \Delta X_{\mathrm{B}n}}{n};$$

$$\Delta Y_{\mathrm{B}1} = \frac{\Delta Y_{\mathrm{B}1} + \Delta Y_{\mathrm{B}2} + \cdots + \Delta Y_{\mathrm{B}n}}{n}; \qquad (2)$$

$$\Delta Z_{\mathrm{B}1} = \frac{\Delta Z_{\mathrm{B}1} + \Delta Z_{\mathrm{B}2} + \cdots + \Delta Z_{\mathrm{B}n}}{n}.$$

In presented formulas ΔX_{Ai}, ΔY_{Ai}, ΔZ_{Ai}, ΔX_{Bi}, ΔY_{Bi}, the offset by the X, Y, and Z coordinates of the reference points on the surfaces under the front support of the spindle (points Ai) and under the rear support of the spindle (points Bi); n – is the number of base points on the surface of the spindle support (for the scheme shown in Figure 4, n = 4).

The displacement along the Z-axis of the front support (DZB) and the corresponding displacements of the reference points on the surface under this resistance are not determined. This support is usually floating.

Based on displacements of spindle supports, the displacements of the spindle head body to the cutting area, were determined (point D, Figure 6). The calculation was carried out for geometric reasons (Figure 6). As the deformation is determined not for the spindle, but for the housing, the spindle axis is considered as a segment passing through the centers of the spindle supports, the displacements to the cutting zone are calculated on the basis of the rotations and displacements of the given segment caused by the displacements of the supports. Since the rear support is usually made floating (no fixation in the axial direction), the displacement of the cutting zone in the axial direction is determined based on the corresponding displacement of the front support.

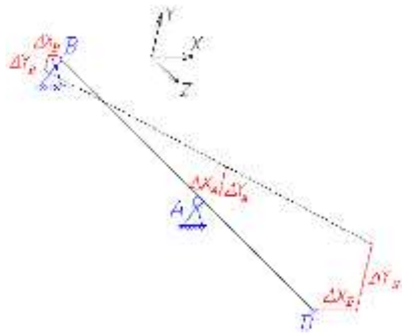

Figure 6. Scheme of calculation of displacements of the body of the spindle headstock of the cutting zone

Based on the geometric dependencies shown in Figure 6, the following formulas were obtained to determine the offsets by the X, Y, and Z coordinates of the cutting zone:

$$\Delta X_D = \Delta X_D + \left|(\Delta X_A - \Delta X_B)\frac{\mathrm{L_{AD}}}{\mathrm{L_{AB}}}\right|;$$

$$\Delta Y_D = \Delta Y_D + \left|(\Delta Y_A - \Delta Y_B)\frac{\mathrm{L_{AD}}}{\mathrm{L_{AB}}}\right|; \qquad (3)$$

$$\Delta Z_{\mathrm{D}} = \Delta Z_{\mathrm{A}}.$$

The components of the machining errors due to the deformations of the structure that are calculated under the action of the cutting forces are calculated based on the displacements of the cutting zone:

$$\Delta D_{PK} = 2\Delta X_D \quad \text{(for longitudinal processing);} \qquad (4)$$

$$\Delta L_{PK} = -\Delta Z_D \quad \text{(for transverse processing).} \qquad (5)$$

The following info describes the procedure for determining the spatial position of the transverse support. The spatial position of the longitudinal support is defined similarly.

Based on the assumption that there is no influence of deformation of the structure, which is calculated on the deformation of other units of the machine. Also, the calculated components of the machining errors are due only to deformations of the base surfaces of the guides and housings of the support screws, the support in the calculation of the components of the machining errors can be considered as a solid, the spatial position of which is determined by the displacements of the base points on the surfaces of the guides and bodies of the support screws.

First of all, the spatial position of the housing of the screw of the support is determined, which provides axial fixation of the screw (Figure 7). The displacement of the center of the support surface of the housing of the support of the screw of the support (points $A_{КОХВ}$) along the X axis is calculated as the arithmetic mean of the corresponding displacements of the base points A1, A2, A3, A4:

$$U_{AKOXBXD} = \frac{U_{A1X} + U_{A2X} + U_{A3X} + U_{A4X}}{4}; \qquad (6)$$

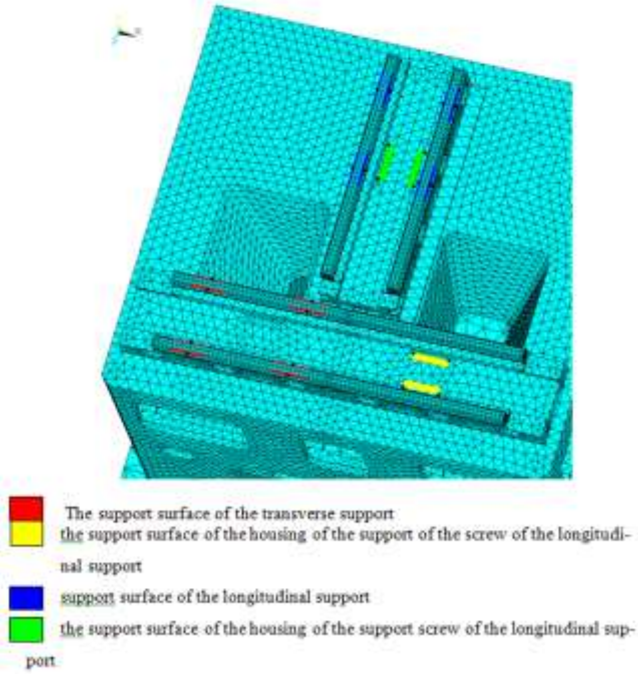

Figure 7. Points used as bases in determining the spatial position of supports

The angle of rotation of the housing of the screw around the Z axis is calculated as the arithmetic mean of the angles of rotation of segments A1A2 and A3A4 around this axis:

$$\alpha_{KOXBZ} = \frac{\alpha_{A1A2Z} + \alpha_{A3A4Z}}{2}; \qquad (7)$$

The remaining spatial coordinates of the support screw housing (two displacements and two rotation angles) are not calculated, as they do not affect the axial displacement of the screw.

Based on the spatial position of the housing, the displacement of the support screw in the axial direction (along the X axis) is determined. Because in the machines of this design, each of the running screws has an axial fixation in only one support. The axial displacement of the screw-nut transmission is assumed to be equal to the axial displacement of the support.

The axial displacements of the transmission of the screw-nut determine the dis-placement of the support along the X axis (along the guides), since the ability to move the support along the guides does not allow the influence of the displacements of the guides along the X axis on the displacement of the support.

The offset of the caliper at the point $B_{СУП}$ on the X-axis ($U_{BСУПX}$) is determined based on the axial displacement of the screw-nut transmission and the angle of rotation of the support around the Z_{axis} ($\alpha_{СУПZ}$). The calculation scheme does not con-sider the displacements due to the propulsive of the screw-nut transmission, the axial displacement of the transmission can be taken to be equal to the offset on the axis X of the housing support of the screw (UAKOHVX).

Based on the spatial position of the support and the location of the cutting zone, it is possible to calculate the displacement of the support in the cutting zone. The offsets are reduced to the point on the spindle axis. However, to provide greater versatility of the calculation method, it was necessary that the radius of the workpiece was very small compared to other sizes of the calculated design.

5. Conclusions

The basic technical and technological requirements for geometrical and finite element models of body parts of metal cutting machines used in the construction of the calculation scheme are formulated. The ways of taking into account in the calculation scheme of different conditions of fixing and loading, characteristic for the body parts of metal-cutting machines, are offered.

Macros have been developed in the embedded ANSYS finite-element analysis programming language. They provide the calculation of the force displacements reduced to the cutting zone based on the displacements of the base points (obtained by calculating the stress-strain state in ANSYS).

The developed approach makes it possible to calculate for any possible variant of the location of the moving units and the cutting zone, as well as to automatically perform a series of calculations for a given set of such variants.

The proposed method of designing metal-cutting machines ensures the obtaining of the dimensions of the body parts and their individual structural elements by means of parametric optimization. This makes it possible to reduce the effect of deformation of the body parts on the accuracy of the machine. The task of optimization is to find such thicknesses of the walls of the housing at which it would have maximum rigidity while storing its original mass.

It should be noted that many aspects of the approach to finite element calculations of machine body parts can also be used for machines of other types, as well as for dynamic and thermal calculations, if techniques for calculating these processes are developed.

The implemented approach to design and calculation of power displacements of body parts of metal-cutting machines with the help of CAD and CAE technologies provides much less expense of computing resources and time.

References

[1] Redko, R., Zabolotnyi, O., Redko, O., Savchuk, S., Kovalchuk, V. Improvement of Manufacturing Technology and Recovery of Clamping Collets for Lathe Automats. In: Ivanov V. et al. (eds) Advances in Design, Simulation and Manufacturing II. DSMIE 2019. Lecture Notes in Mechanical Engineering. Springer, Cham (2019).

[2] Sychuk, V., Zabolotnyi, O., McMillan, A.: Developing New Design and Investigating Porous Nozzles for Abrasive Jet Machine. Powder Metallurgy and Metal Ceramics 9-10 (53), 600-605 (2015).

[3] Vilchinskij, M.: The analysis of factors which determine the design of metal cutting machine tools' body parts. Student scientific bulletin vol. 31, 27-31 (2019).

[4] Naresh, D., Alam, M.: Machining and machine tools book. Genius Publications, (2014).

[5] Xie, J., Liu, F., Huang, J.: Mapping acquisition of loading loss coefficient of main driving system of machine tools. ProcIMechE, Part B: Engineering Manufacture 2016,vol. 230,pp. 1264–1271 (2016).

[6] Liang, S., Shih, A.: Analysis of machining and machine tools. Springer, (2016).

[7] Bochkov, V., Silin, R., Gavrilchenko, O.: Calculation and design of metal-cutting machine tools.Beskid Bid, Lviv (2008).

[8] Kuznetsov,Yu., Dmitriev, D.: Realization of the conception of frame configuration machine-tools. Bulletin NTUU «KPI». vol. 3 (78), pp. 26-32 (2016).

[9] Bazhenov V., Sakharov A., Melnichenko G., Cherny S.: The finite element method in problems of mechanics. K .: KDTUBA, – 368 p. (1994).

[10] Sherstiuk D., Kulik A., Gladkiy M.: The prospect of using the finite element metod and ANSYS for mathematical modelling of thermo-mechanical calibration large axisymmetric structures with high requirements for the geometric accuracy. Optimization of production processes and technical control in machine building and instrument production. Bulletin of National University "Lviv Polytechnic". № 760, pp. 39-51(2013).

[11] Landrein P. Influence of some test parameters on specimen loading determination methods in instrumented Charpy impact tests / P. Landrein, T. Lorriot, L. Guillaumat // Ibid, 2001. pp. 65-71.