



## **MANUFACTURING ENGINEERING AND AUTOMATED PROCESSES**

### **МАШИНОБУДУВАННЯ, АВТОМАТИЗАЦІЯ ВИРОБНИЦТВА ТА ПРОЦЕСИ МЕХАНІЧНОЇ ОБРОБКИ**

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#### **SHAPE FORMING SYSTEM MODEL OF LATHES TWO-CARRIAGE TOOL SYSTEMS**

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**Summary.** *The paper deals with the mathematical model development of shape forming of lathes with two carriage tool systems. According to the examining of shape forming system parallel as well as shape forming codes отримано the shape forming function model is developed regarding to the single-spindle two-carriage CNC lathe for performing different combinations of parallel surfaces turning. The estimation is given towards the shape forming possibilities spectrum of the single-spindle two-carriage CNC lathes. The developed shape forming function model is a basic one in the model structure of the output accuracy of modern CNC lathes for multitool machining.*

**Key words:** *lathe, form shaping, form-shaping function, turning, mathematical model, tool system, two carriage system.*

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**Problem setting.** The present-day stage of machine manufacturing development is characterized by wide use of CNC machine tools and machine tool complexes. The productivity efficiency improving problem of modern CNC lathes and machine tool complexes on their base in conditions of high-variety manufacturing and high precision parts machining is of actual priority for the majority of production enterprises.

Multi tool simultaneous machining of a single or several surfaces is among the effective methods of turning machining productivity improving, in particular – the parallel double tool turning machining [1]. Such machining efficiency enhancement potential from two carriage systems with independent control is in a rational correspondence of work piece surface (surfaces) machining with mutual spindle rotation speed. This rational combination of simultaneous turning machining is strongly influenced by the errors occurring in the process of such machining. And the errors depend on the tools space location and simultaneous influence of all cutting forces components from all the tools operating in the machining as well the elastic displacements of lathe shape forming system with respect to all the coordinates, machine geometric accuracy, etc. In this way the model development of the modern CNC lathes result accuracy with shape forming system model in its structure is a scientific problem of high actuality.

The paper is concerned with the scientific topics dealing with design theory development and research of highly efficient and resource saving methods of automatized turning machining and new high speed manufacturing equipment.

**Analysis of the known research results.** Numerous scientific papers using different scientific approaches deal with the accuracy calculation problems of the technological machining system. This task is of advanced actuality in solving problems of the accuracy control, evaluation of machine tool accuracy at the design stage, as well as defining several parameters of the machining accuracy, etc. Of these the calculating method of resulting machining error can be distinguished. This method is based on the development of the equivalent diagram of the technological machining system with next reduction of the tool cutting edge points coordinates to the coordinate system developed according to the work piece technological bases [2].

Variation method is principally another one allowing to develop the machine accuracy balance taking into account numerous errors sources [3, 4], Using in it the fundamental error quality that is its especially small value in comparison with the nominal dimension – allows to determine the analytic expressions correlating in an explicit form and implicitly the input and the output accuracy characteristics of technological machining system. This method enables evaluation of the machining part surface error even at the design process stage. According to [3] the model of machine tool shape forming system is a structural part of the machine resulting accuracy model. So the shape forming system model represents the connection between the coordinates of the tool cutting edge points in the cutting tool system and the coordinates of the same points in the machining work piece system of axes.

This method was taken further in the paper [5] in the methodology developing of metal cutting machine tools structural and parametric synthesis and in the paper [6] in developing the methodic complex providing parametric reliability of technological equipment. It also served as a base in machining accuracy evaluation of parts using machine tools with block-to-block structural configuration types [7 – 9].

**Paper objective.** It is basing on the analysis of the shape forming processes as well as mathematical coordinates transforming techniques to develop the shape forming model of the two carriage single spindle CNC lathes to provide the parallel turning machining. The mentioned model is a part of the model of their resulting accuracy. It is also necessary to evaluate the shape forming possibilities of such lathes.

**Task setting. The model of shape forming system.** Surfaces shape forming along with cutting is the main work process in the metal cutting machine tools. The model of shape forming system composes according to the structure of machine units as well as their motions description and mathematically represents in a form of shape forming function [3, 4]. The important elements of the shape forming system appears as forming segments each of them having a local system of axes and connections between adjacent segments. The segment of the shape forming system arises as a conjunction of machine units and other elements of technological system. Their displacements out of each other in the operating process of the machine tool are nominally non-existent [3]. The machining work part and the cutting tool serves as the end segments of the shape forming system. According to the mark of presence or non-existence of kinematic links between the segments it is possible to differentiate the chain (block-to-block) structure of the shape forming system as well as parallel shape forming system structure which presents as conjunction of chains with even a single mutual segment [10]. Modern CNC lathes with double carriage tool systems have a parallel structure of shape forming system. Fig. 1 shows configuration structures and the parallel structure of shape forming systems of main types of single spindle double carriage CNC lathes for chuck machining with two independently controlled tool carriages.

The mutual segments presence in the shape forming system of parallel action of two carriage single spindle CNC lathes leads to the interaction of the shape forming system segments. This can be definitely expressed in the mutual influence of the processes performing in the different cutting zones. Let us consider the process of shape forming

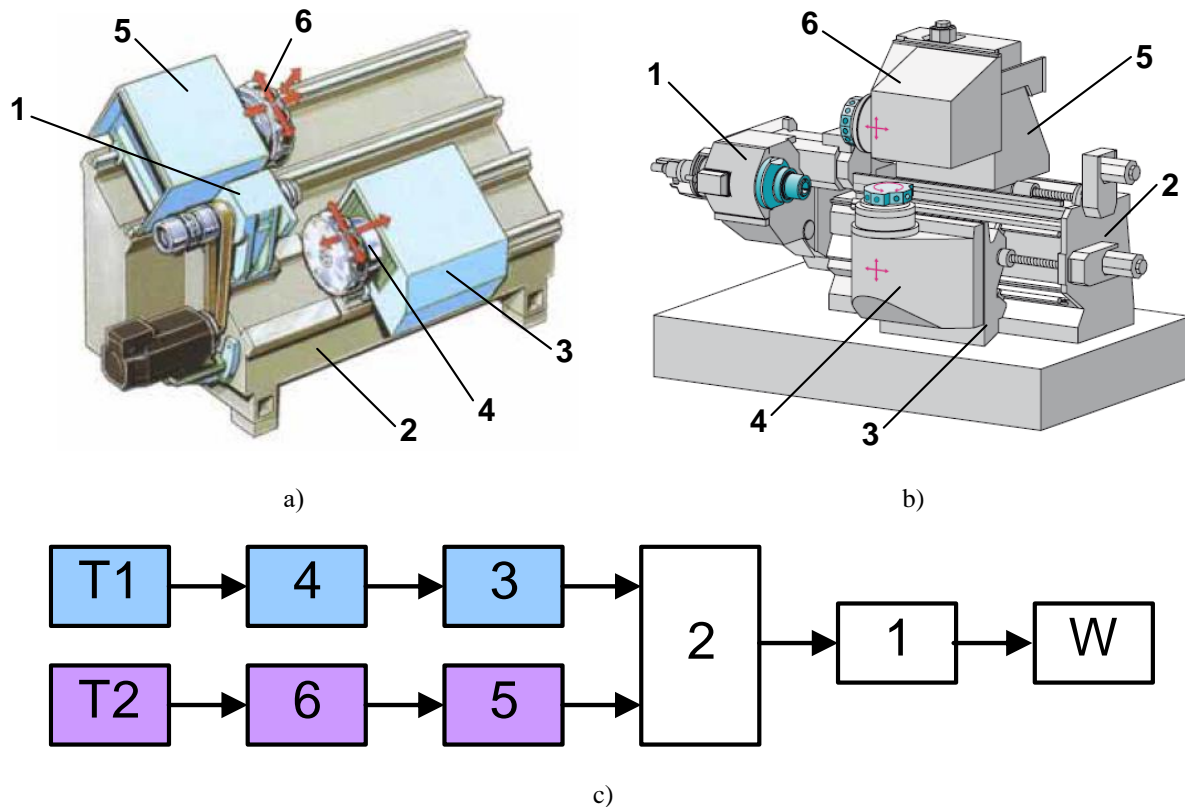
function construction as a formal operation of making correlation between the work piece and tools systems of axes.

For multi tool machining the shape forming function is a set of functions [10, 11]

$$\bar{r}_0 = \prod_{i=1}^l A_{i-1,i}^{k_i} \bar{r}_l \quad (1)$$

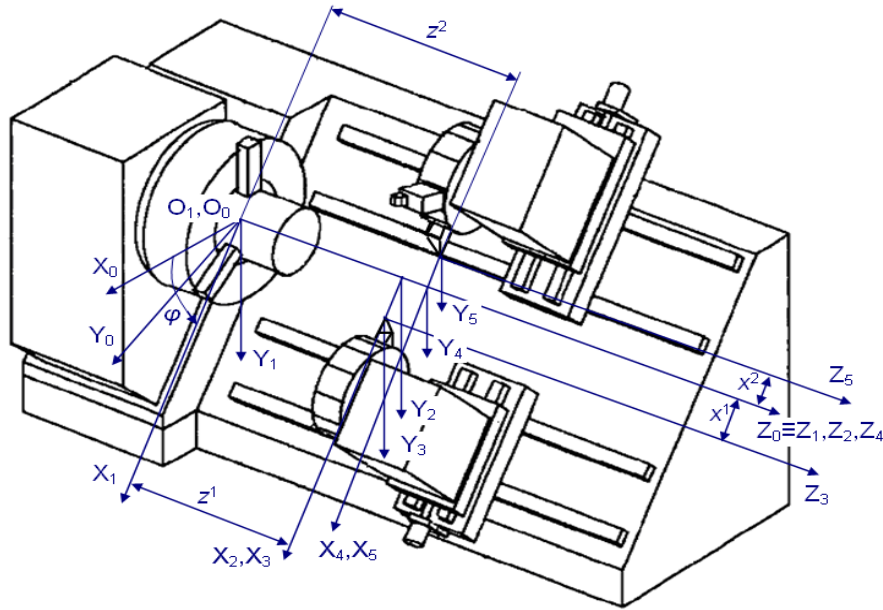
in which  $\bar{r}_l = (x_l, y_l, z_l, 1)^T$  is a radius-vector of cutting tool points;  $\bar{r}_0 = (x_0, y_0, z_0, 1)^T$  – radius-vector of cutting tool points in the work piece system of axes;  $l$  – number of segments of shape forming system;  $\prod_{i=1}^l A_{i-1,i}^{k_i}$  – general matrix of coordinates transforming;  $k_i$  – coordinate code of the  $i$  segment of the shape forming system.

This set of functions makes a correlation between any end segments of shape forming system parallel structure of single spindle double carriage CNC lathes (Fig. 1).



**Figure 1.** Configuration structures (a, b) and shape forming systems parallel structure (c) of main types of two carriage single spindle CNC lathes: 1 – spindle box with spindle unit and work piece; 2 – lathe bed; 3,5 – longitudinal bottom and top carriages correspondingly; T1 and T2 – turning cutting tools for bottom and top carriages correspondingly; W – work piece to be machined

Let us consider the shape forming structure of single spindle two carriage CNC lathe (Fig. 2). Both surfaces that are being machined are located on the same work piece that serves as a zero segment of the shape forming system. Then the coordinate code of the shape forming system for both of its branches is a codes composition of displacement matrix and rotation matrix,  $K_1 = K_2 = 631$  [3].



**Figure 2.** Shape forming system of single spindle two carriage CNC lathe

According to the discussed description of the shape forming process as well as coordinate code of the shape forming system for its both branches the shape forming function for the shape forming system of parallel action looks like

$$\begin{cases} \overline{r_{01}} = A_{01}^6(\varphi) \cdot A_{12}^3(z^1) \cdot A_{23}^1(x^1) \cdot \overline{r_{31}} \\ \overline{r_{02}} = A_{01}^6(\varphi) \cdot A_{12}^3(z^2) \cdot A_{23}^1(x^2) \cdot \overline{r_{32}} \end{cases} \quad (2)$$

in which  $\overline{r_{31}}, \overline{r_{32}}$  – radius-vectors of first and second tools points correspondingly;  $\overline{r_{01}}, \overline{r_{02}}$  – radius-vectors of first and second tools points in the work piece system of axes;  $A_{01}^6(\varphi)$  – matrix of rotation about axis  $Z$ ;  $A_{12}^3(z^1), A_{12}^3(z^2)$  – matrixes of displacements along an axis  $Z$ ;  $A_{23}^1(x^1), A_{23}^1(x^2)$  – matrixes of displacements along an axis  $X$ .

Assuming both tools as single point cutting tools  $\overline{r_{31}} = \overline{e^4} = (0,0,0,1)^T$ ,  $\overline{r_{32}} = \overline{e^4} = (0,0,0,1)^T$  and plugging matrixes of coordinate transforming in (2) we shall have as result

$$\begin{cases} \overline{r_{01}} = [x^1 \cos(\varphi), x^1 \sin(\varphi), z^1, 1]^T \\ \overline{r_{02}} = [x^2 \cos(\varphi), x^2 \sin(\varphi), z^2, 1]^T \end{cases} \quad (3)$$

**Analysis of machine tool shape forming capabilities.** The received shape forming system function (3) gives also a possibility to evaluate the machine tool shape forming capabilities that are the technological machining schemes possible to realize. The shape forming system function (3) shows that in single spindle two carriage CNC lathes five shape forming motions are outlined: spindle rotation (coordinate  $\varphi$ ); longitudinal ( $z^1$ ) and cross

( $x^1$ ) movements of bottom tool system; longitudinal ( $z^2$ ) and cross  $x^2$  movements of top tool system.

Let us discuss the external turning with single point cutting tools when the rounding connections ( $L_{oz}$ ) and hidden connections ( $L_{np}$ ) are of nonexistence [3], that is  $L_{oz} = L_{np} = 0$ . The number of segments performing the shape forming for both of parallel branches of shape forming system is equal to  $n = 3$ , and the number of independent variables in the point shape forming is equal to  $m = 0$ . Then the number of functional links for each parallel branch can be defined from the dependence [3]

$$L_{\phi} = n + m - 2 - (L_{oz} + L_{np}) = 3 + 2 - 2 - (0 + 0) = 1 \tag{4}$$

So a single link is imposed on the shape forming motions of either parallel branches of the shape forming system. According to [3] the maximum number of links for either of branches is equal to  $a_{max} = 7$ , and the number of no permitted links is  $a_z = 1$ , because it is forbidden to stop spindle in the machine tool. In this way the number of schemes of external turning machining with first and second single point cutting tools can be derived as:  $a_1 = a_{max} - a_z = 7 - 1 = 6$ ,  $a_2 = a_{max} - a_z = 7 - 1 = 6$ .

Having regard to the above the schemes combinations are obtained for different surfaces external turning machining with two point tools using single spindle double carriage CNC lathes. These combinations are represented in the Table 1.

The given schemes were obtained in the next way: combination of under run stops of two among four carriages in the given positions (4 schemes); combination of under run stops of one among four carriages in the given positions and links combination between two movements in the first and in the second branches of shape forming (12 schemes); combination of under run stops of one among four carriages in the given positions and links combination of all of three movements in the first and in the second branches of shape forming (4 schemes); links combination between two among three movements in the first and in the second branches of shape forming (9 schemes); links combination between two movements in the first and in the second branches of shape forming and links combination between three movements in the first and in the second branches of shape forming (6 schemes); links combination between three movements in the first and in the second branches of shape forming (1 scheme).

**Table 1**

Schemes combinations of simultaneous external chuck turning machining of different surfaces using single point double carriage CNC lathes

Relation between variables in equation (3)	$x_2 = 0,5D_1$	$z_2 = C_2$	$x_2 = f(z_2)$	$x_2 = \rho_2(\varphi)$	$z_2 = z_2(\varphi)$	$z_2 = z_2(x_2, \varphi)$
1	2	3	4	5	6	7
$x_1 = 0,5D_1$	Machining two cylindrical surfaces	Machining cylindrical surface and face	Machining cylindrical and profiled surfaces	Machining cylindrical surface and a cam with generating line	Machining cylindrical and helical surfaces	Machining cylindrical and free-form surfaces

(to be continued)

1	2	3	4	5	6	7
$z_1 = C_1$	Machining face and cylindrical surface	Machining two face	Machining face and profiled surfaces	Machining face and a cam with generating line	Machining face and helical surface	Machining face and free-form surfaces
$x_1 = f(z_1)$	Machining profiled and cylindrical surfaces	Machining profiled surface and a face	Machining two profiled surfaces	Machining profiled surface and a cam with generating line	Machining profiled and helical surfaces	Machining profiled and free-form surfaces
$x_1 = \rho_1(\varphi)$	Machining a cam with generating line and cylindrical surface	Machining a cam with generating line and a face	Machining a cam with generating line and profiled surface	Machining two cams with generating line	Machining a cam with generating line and helical surface	Machining a cam with generating line and free-form surface
$z_1 = z_1(\varphi)$	Machining helical and cylindrical surfaces	Machining helical surface and a face	Machining helical and profiled surfaces	Machining helical surface and a cam with generating line	Machining two helical surfaces	Machining helical and free-form surfaces
$z_1 = z_1(x_1, \varphi)$	Machining free-form and cylindrical surfaces	Machining free-form surface and a face	Machining free-form and profiled surfaces	Machining free-form surface and a cam with generating line	Machining free-form and helical surfaces	Machining two free-form surfaces
Symbols: $D_1, D_2$ – cylinder diameters; $C_1, C_2$ k – distances from faces to the beginning of the axis system; $f(z_1), f(z_2)$ – current radiuses of rotation surfaces in distances $z_1$ i $z_2$ from the beginning of the axis system; $\rho_1(\varphi), \rho_2(\varphi)$ – cams polar radiuses; $z_1(\varphi) = p_1\varphi$ , $z_2(\varphi) = p_2\varphi$ , де $p_1$ i $p_2$ – parameters of helical lines						

Thus in general we have 36 schemes of different surfaces turning machining with two point cutting tools using single spindle double carriage CNC lathes. For another thing in machining one and the same surface with two point tools (for example cylindrical,  $x_1 = x_2 = 0,5 D$ ) using single spindle double carriage CNC lathes the 6 schemes of simultaneous turning machining exist additionally.

By applying the given principle the scheme combinations of internal machining were received as well as the schemes of internal and external different surfaces machining by two point tools using single spindle double carriage CNC lathes.

**Conclusions.** It have determined that for performing the simultaneous turning machining work piece surfaces with a few cutting tools the shape forming system of the double carriage CNC lathes has a parallel structure with mutual segments. The basic units

with a spindle and work piece act as these segments. On the ground of considering of the shape forming system parallel structure as well as shape forming coordinate codes the shape forming function model was developed regarding a single spindle double carriage CNC lathe for performing parallel surfaces turning machining. The received of machine tool shape forming system as well as the links system analysis allowed obtaining the list of all possible surfaces combinations to be machined. In this way it comes possible to evaluate the spectrum of shape forming capabilities of single spindle double carriage CNC lathes. The given shape forming function is a basic one in the resulting accuracy structure model of modern single spindle double carriage CNC lathes and enables to determine their shape forming possibilities.

On the assumption of received shape forming function model with regard to single spindle double carriage CNC lathe in the near future it is planned to take an evaluation of its output accuracy in the machining process of internal and external rotation surfaces taking account to scheme combinations of parallel turning machining.

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# МОДЕЛЬ ФОРМОУТВОРЮЮЧОЇ СИСТЕМИ ТОКАРНИХ ВЕРСТАТІВ ІЗ ДВОСУПОРТНИМИ ІНСТРУМЕНТАЛЬНИМИ СИСТЕМАМИ

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**Резюме.** Стаття присвячена розробленню математичної моделі формоутворюючої системи токарних верстатів зі двосупортними інструментальними системами. Встановлено, що для здійснення одночасної токарної обробки поверхонь заготовки кількома різальними інструментами формоутворююча система двосупортних токарних верстатів з ЧПК має паралельну структуру зі спільними ланками, якими є базові вузли із шпинделем та оброблюваною деталлю. Показано, що наявність у такій формоутворюючій системі загальних елементів призводить до взаємодії ланок формоутворюючої системи. Вона виражається у впливі процесів, які проходять у різних зонах різання один на одного. Побудову функції формоутворення розглянуто як формальну операцію встановлення зв'язку між системами координат заготовки й інструментів. На основі цього та розгляду паралельної структури формоутворюючої системи й координатних кодів формоутворення отримано модель функції формоутворення одношпиндельного двосупортного токарного верстата з ЧПК для здійснення різних комбінацій паралельної токарної обробки поверхонь. Ці комбінації стосуються схем внутрішньої, а також внутрішньої та зовнішньої токарної обробки різних поверхонь двома точковими інструментами на одношпиндельних двосупортних токарних верстатах з ЧПК. Оцінено спектр формоутворюючих можливостей одношпиндельних двосупортних токарних верстатів з ЧПК. Показано, що різновиди схем обробки при використанні точкового інструменту залежать від комбінації різних рухів формоутворюючої системи верстата. Отримана модель функції формоутворення є основою в структурі моделі вихідної точності сучасних токарних верстатів з ЧПК для багатоінструментальної обробки.

**Ключові слова:** токарний верстат, формоутворення, функція формоутворення, точіння, математична модель, інструментальна система, двосупортна система.

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