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CONFIGURATIONS AND MODULARIZATION GRADE OF SOME CNC TURNING MACHINES

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Abstract: *This paper presents an analysis regarding the configuration and structure of the kinematic couples of rotation and translation of some mono and multiaxes lathes with increased level of universality and flexibility built in modular approach. The schematic representations use usual symbols and notations assigned to the structure elements and generating assemblies and also the CNC axes. For each representation a structural formula is supplied. On the basis of the schematic and structural formula the method of transformation for two closed structure elements is proposed. Using the same approach, the matrix of transformation attached two the two branches of tool and workpiece connected in a fictitious mechanism T-WP. The results of the application consist of the parametric equations of the generated trajectory that represents the generatrix and directrix curves that define the machined surface. The presented analysis shows that the variants of modular lathes enable the rapid change of the machine configuration depending on the generating technological necessities of different surfaces.*

Key words: *CNC lathe, kinematic couple, generation motions, CNC axis, structure element, basic modules, generated trajectory.*

1. INTRODUCTION

The modularization applied to numerous fields of the machine construction, equipment and installations industries is determined by the dimensional diversification of these products having the same functional role, but with different sizes. In the machine tools and deforming machines fields there are a lot of applications of modularization, being a necessity of fulfilling the requirements regarding their configuration and reconfiguration [10, 13].

The effects of modularization have in view: structure element optimization form the point of view design and processing technologies, decreasing the ratio machine size and a basic geometric dimension that defines the piece, size variety extension, increasing of the flexibility and productivity, reducing the costs, and possibility of reconfiguration.

The analysis of the principles that define the modular conception of the machine tools id presented in detail in many specialty papers [1, 2, 4, 9, 15, and 20]. Thus, the paper [4] emphasizes exclusively for milling machines and milling machining centres numerous possible variants resulted through selective choice of minimum 3 of the 8 basic modules grouped in machine structure: driving (from the bed to the main spindle-tool) and supporting and driving the workpiece. Other point of view regarding structural configuration having on the basis a method based on graph configuration is presented by [8].

In addition, we consider that the two components tool (*T*) and workpiece (*Wp*) are the elements of the fictitious mechanism (*FM*) defined by Botez [5].

The fictitious mechanism piece-tool, defined for the first time by Emil Botez [5] can be extended for all types of closed or opened kinematic chains. We accept that the fictive mechanism workpiece-tool is the one that appears during the generation of surfaces, as there is a real mechanism between the tool (*T*) and workpiece (*Wp*).

The kinematic chain produces at its end a relative translation *T* or rotation *R* motion between two elements of the robot or machine tool connected by a couple (joint).

For the machines that at a moment of time cut one workpiece using only one tool, this *FM* has an input and an output; for the machines that cut a single workpiece with several tools, the *FM* has several inputs and outputs. Regarding these considerations, one proposes the extension of some methods used in kinematic study in industrial robots in machine tool kinematic analysis (in our case with application to lathes). Some studies in this field are known for up to 5 axes CNC machine tools [4].

For a CNC machine tool, the structural formulae are:

$$C_i^j\,(T_i\,/\,R_j) - O - C_m{}^n\,(T_m\,/\,R_n)\,, \qquad (1)$$

where *O* is the fixed element (bed), *C* are structure elements with rotary pr translation motion (main spindle – *MS,* slides – *S*), *T/R* – motions in joints.

2. ASPECTS OF MODULARIZATION

Conception and fabrication in modular systems of the machine tools are studied and applied more and more by different companies in the field [20]. Modularization comprises the machine tool in its entireness [9, 11, 18], namely: structure elements, headstock, main spindle, slides, electric motors, and mechanism lead screw-nut, revolver heads, tailstock, heads with angular positioning, turrets, multi-axes units, axis for slope work, etc. Also, modular variants are realized for systems of storage and transfer of workpieces and tools, clamping and driving devices for workpieces and tools, other elements and systems (greasing, cooling, chip transportation).

In this way, modularization enables the creation of a great number of configurations for different machine tools having functional characteristics in wide ranges (sizes, strokes, speeds, and precision) and a number of numerically controlled axes [20]. Thus, the technological possibilities and the grade of flexibility of the machine or system in which it is integrated are extended.

From this point of view the work [7] states four levels of modularization defined by:

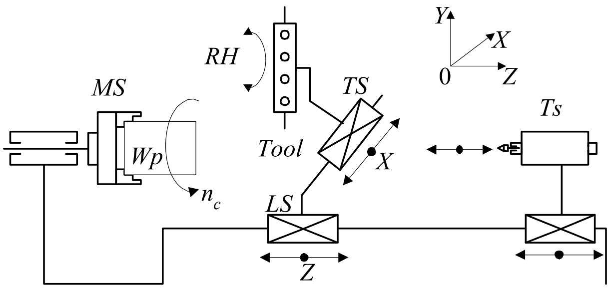
- geometric similar semi-products;
- existence of main spindle (universal, rotational, bi-positional);
- diverse grades of automatization, grade of complex automatisation for machines and systems that machine in imposed conditions especially by the production type.

3. CONFIGURATIONS OF SOME CNC LATHES

The companies that produce CNC turning machines have launched on the market numerous variants having configurations, kinematic structures and functional characteristics of very different. Firstly, to the lathes with two axes (*X* and *Z*) the axis *C* (rotation of main spindle for feed and positioning motions) was added and then the axis *Y* (perpendicular translation on the work plane *XOZ*). Also, the lathes with two coaxial, symmetrical main spindles in integrated construction appeared that enable the machining at both end by transfer between them. Accordingly, some slides and assemblies of revolver heads were adapted. In most of lathes, the main spindles are in integrated variant and enable processing by drilling, milling, threading, or grinding. Another category is represented by the machine with mains spindles whose angular position in plane *XOY* is numerically controlled (B axes), being automated supplied with tools from the tool magazine.

Thus, the numerically controlled axes have increased, namely: for rotary motions (axes C_1 and C_2 or *B*) and for feed and positioning motions axes Z_2, *W*.

The analysis of these machines is done on the basis of the well know criteria in the literature, namely: number and position of main spindles, number of the numerically controlled axes. They determine the kinematic structure of the lathe, obviously a main kinematic chain corresponding to a main spindle. The main kinematic chain is achieved in modern variant of integrated type. In older constructions it is constituted of electric motor with continuous adjustable speed and a gear box with 2, 3 or 4 steps. The CNC axes of the machine determine the number of feed/positioning kinematic chains. The positioning motions on linear trajectories are obtained with continuous adjustable speed motors and mechanism lead-screw-nut. Some companies present modern variants for driving with linear electric motors. For motions on circular trajectories, electric motors integrated with the driven assembly are used or variants with kinematic chain composed of electric motor and reducer (synchronous transmission, gearing).



R(MS) – O – T(LS) – T(TS)

Fig. 1. Lathe with two CNC axes.

Lathes with two numerically controlled axes. This category is mostly spread and has possibilities of machining by frontal turning (motion of the tool on the *X* axis), cylindrical turning (*Z* axis), conical or profiled turning (*X* and *Z* axes) by linear and/or circular interpolation, threading.

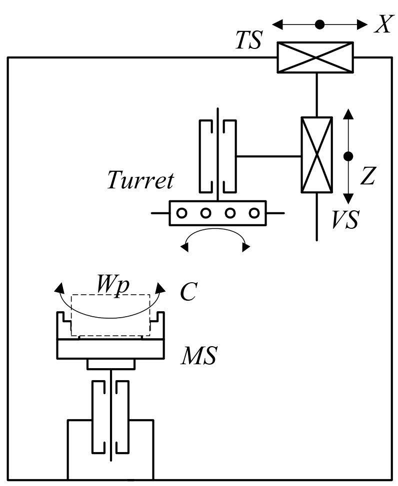
Figure 1 shows the main rotary motion *R* with the speed n_c performed by the tool *S* in radial direction (axis *X*), or longitudinal direction respectively (axis *Z*), with the speeds w_r and w_L respectively. For the feed motions the translations couples are considered.

These lathes are mainly uses for processing workpieces of shaft type between points, using the tailstock with positioning motion on the bed guide ways and having or not the axis *W*.

In case for which there are two main spindles, a revolver head assembly is oriented to the main spindle, the other to the right main spindle.

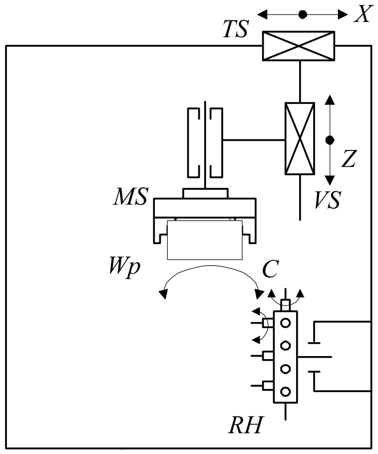
Lathes with three numerically controlled axes. The third numerically controlled axis (Fig. 2) (axis *C*) is that belonging to the main spindle used for feed and angular positioning motions for processing by drilling, milling, grinding with rotary tool in the revolver head.

Figure 3 shows another configuration of a vertical turning machine in which the translation motion on the axis *Z* is executed by the assembly of the main spindle *MS* (R). Thus, for turning processes the main motion with he speed n_c is used and also linear motions on the axes *X* and *Z* independently or simultaneously. The utilization of the axis *C* enables additional possibilities of



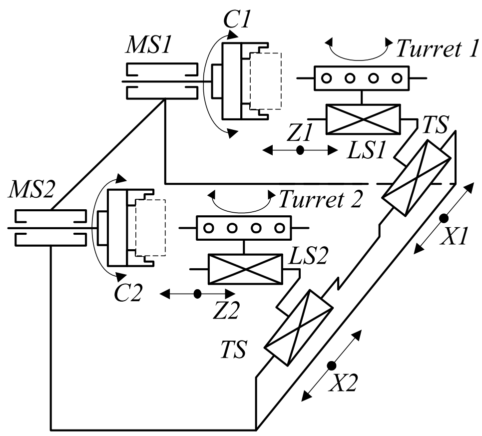
R(MS) – O – T(TS) – T(VS)

Fig. 2. Vertical lathe with three CNC axes.



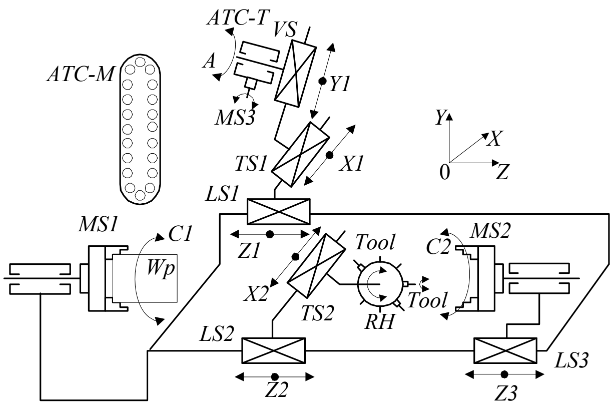
O – T(TS) – T(VS) – R(MS)

Fig. 3. Vertical lathe with three CNC axes.



$$\begin{array}{l|c|l} R(MS1) - & O - & T(TS1) - T(LS1) \\ R(MS2) - & & T(TS2) - T(LS2) \end{array}$$

Fig. 5. Frontal lathe with six CNC axes.



$$\begin{array}{l|c|l} R(MS1) - & O - & T(LS1) - T(TS1) - T(VS1) - R(ATC\text{-}T) - R(Tool) \\ R(MS2) - T(LS3) - & & T(LS2) - T(TS2) - T(VS2) - \,|\, R(Tool) \end{array}$$

Fig. 6.. Lathe with two main coaxial symmetrical spindles.

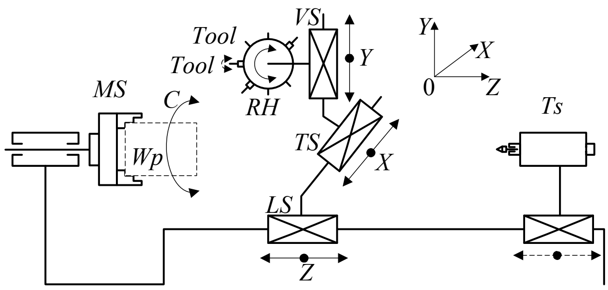
generation of surfaces through drilling, boring, milling, threading, grinding in angular positions and determined feed speeds of the workpiece *WP* and rotary tool *T* in the revolver head *RH*. The lathes with such a configuration process in individual working posts or integrated in flexible cells of manufacturing systems. In both cases they are enabled with automatic feed systems for semi products having a conveyer and pallets constructed in modular variants.

Lathes with four NC axes. These machine tools are lathes with one or two revolver heads (one placed above and the other under the main spindle axis level – Fig. 4). Each revolver head is mounted on a working support consisting of the two slides – longitudinal (*LS*) and transversal (*ST*) that achieve motions on the axes *X* and *Z* (in addition X_2 and Z_2 in case of lathes with two revolver heads).

The main spindle independently driven has the rotary motion numerically controlled – axis *C* (in case of the lathe with two revolver heads, there are two independent spindles having the axes C_1 and C_2).

In these lathes instead of a tailstock a secondary mains spindle is implemented.

The frontal lathe with six CNC (Fig. 5) axes enable simultaneous processing of two workpieces identical or different namely: the same workpiece machined successively at both ends or two different workpieces machined simultaneously at one end.



$$R(MS) - O - T(LS) - T(TS) - T(VS) \,|\, R(Tool)$$

Fig. 4. Revolver lathe with four CNC axes.

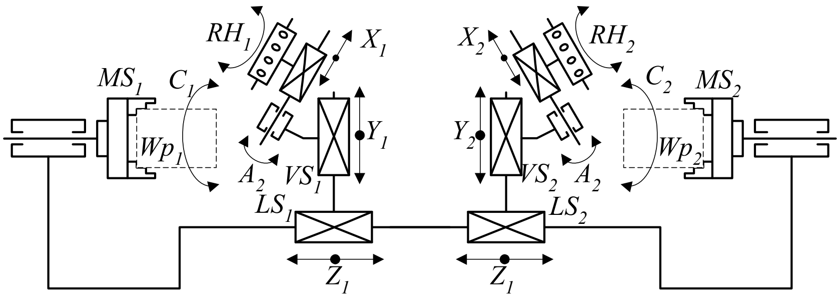
Lathes with eight NC axes. Each main spindle *MS* processes with a working support consisting of the revolver head *RH* mounted on the assembly of the two slides – transversal *TS* and longitudinal *LS*.

The lathe presented in Fig. 6 has eight CNC axes. The right main spindle – MS_2 is placed on a longitudinal slide SL_3 that enables its motion to the left after the machining stop in the main spindle MS_1, for machining the same workpiece without rotating it with 180° between the two operations. The axis *A* together with axis C_1 enables complex surfaces machining.

In other lathes, each revolver head has two (X_1, Z_1), (X_2, Z_2) or three (X_1, Y_1, Z_1), (X_2, Y_2, Z_2) CNC translation axes, eventually one ahs two CNC translation axes, the other one having three.

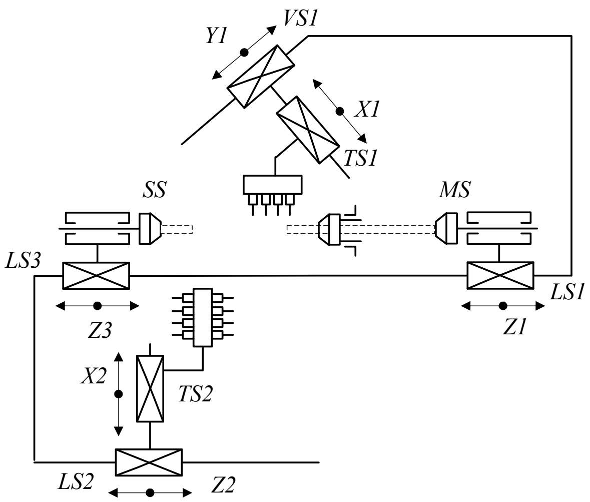
Often, the machine tools producers apply the solution of driving CNC lathes from universal machine from current fabrication. They make some modifications regarding the kinematic structure, driving, implementation of a CNC equipment, and provide them with accessories for increasing their universality.

The lathe in Fig. 7 is in symmetrical construction and has four CNC axes for every main spindle *MS*. Its particularity is that each revolver head can be angularly



$$\begin{array}{l|c|l} \mathrm{R(MS1)} - & \mathrm{O} - & \mathrm{T(LS1) - T(VS1) - R(Head1) - T(IS1)} \\ \mathrm{R(MS2)} - & & \mathrm{T(LS2) - T(VS2) - R(Head2) - T(IS2)} \end{array}$$

Fig. 7. Lathe with two main coaxial symmetrical spindles.



$$\begin{array}{l|c|l} \mathrm{R(MS) - T(LS1)} - & \mathrm{O} - & \mathrm{T(TS1) - T(VS1)} \\ \mathrm{R(SS) - T(LS3)} - & & \mathrm{T(LS2) - T(TS2)} \end{array}$$

Fig. 8. Longitudinal lathe with 6 axes.

positioned with the aid of a CNC axis, that enables the necessary positioning of the tool (rotary) with regard to the workpiece.

For workpieces with small dimensions of shaft type, the multi-tool CNC lathes have been designed from the principle of the automatic longitudinal lathes (Fig. 8). The workpiece has both main and longitudinal feed motions. The workpiece support is achieved by means of a rotary support *RS*. For machining a both ends, the workpiece is taken over before cutting of by a secondary spindle *SS* having a longitudinal motion given by the slide LS_3. The multi-tools holders MTS_1 and MTS_2 allow the machining on radial and both axial directions (MTS_2).

4. POSSIBILITIES OF PROCESSING

The surface *SG* generated by cutting on lathes for every kind of workpiece represents the reunion of different elementary surfaces S_i that compose it:

$$SG = \bigcup_{i=1}^{n} S_i \tag{2}$$

Some of the elementary surfaces are of revolution (cylindrical, conical, helical, exterior or interior profiled) situated on the main spindle axis. Others are plane frontal surfaces, perpendicular or inclined with regard to the main spindle axis. Also, other elementary surfaces have positions defined by an axis or a direction different from the main spindle axis.

The large variety of surfaces means the application of many cutting technological methods, using a diversity of cutting tools with generation and positioning motions having defined directions and speeds.

All these have led to a variety of mono and multi-axes horizontal lathes that can machine workpieces in imposed precision and production conditions.

By adding the axis of rotation *C*, it becomes possible the synchronization with the translation axis *X*, for example in case of milling polygonal surfaces. The synchronization of the axes *Z* and *C* enables also the milling of the helical grooves on a cylindrical surface. In both case, a rotary too is used (mill), driven in main cutting motion by an electric motor included in the revolver head assembly mounted on the slide with motion on the axis *Z*.

Formalism used for kinematic analysis of lathes. These kinds of representations and structural formulae are based on formalisms used in kinematic structural analysis for industrial robots. For example, the Denavit-Hartenberg [12, 16] convention allows the transformation matrix calculation between two reference systems attached to two consecutive elements from robots structure. The positioning of an element relatively to an adjacent one is achieved by attaching a reference system to every element having its index number corresponding to the element number *i*.

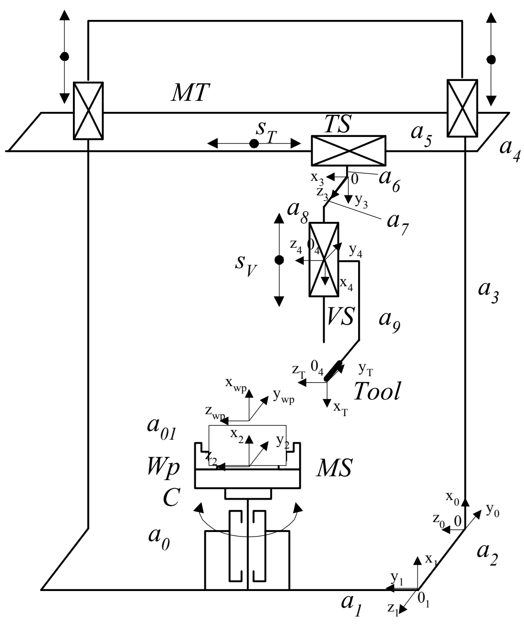
For solving this model, one should know the meaning of the following operators:

- α_i – angle about x_{i-1} axis measured between z_{i-1} and z_i;
- a_i – *distance* along x_{i-1} from the origin O_{i-1} to z_i axis;
- θ_i – angle about z_i axis measured between x_{i-1} and x_i;
- d_i – distance along z_i axis measured between intersection point of x_{i-1} and z_i axes and O_i origin.

The transformation matrix for an entire kinematic branch is the product of the transformation matrix of the reference systems attached to each element of the branch:

$$T_0^n = T_0^1 \cdot T_0^2 \cdot \ldots \, T_{i-1}^i \cdot T_{n-1}^n, \tag{3}$$

where



R(MS) – O – (*MT*) – T(TS) – T(VS)

Fig. 9. Structural configuration of a vertical lathe used in application.

Table 1

Denavit-Hartenberg formalism for the vertical lathe

	Bed-workpiece branch			Bed-tool branch		
Operator	1	2	*Wp*	3	4	*T*
α_i	- 90°	90°	$-\theta_1$	0	0	0
a_i	0	a_0	a_{01}	$a_5 + s_T$	$a_8 + s_V$	a_9
θ_i	0	0	0	90°	90°	0
d_i	a_2	a_1	0	$a_3 - a_7$	a_8	0

$$T_{i-1}^{i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_i \\ \cos\alpha_i \cdot \sin\theta_i & \cos\alpha_i \cdot \cos\theta_i & -\sin\alpha_i & -d_i \cdot \sin\alpha_i \\ \sin\alpha_i \cdot \sin\theta_i & \sin\alpha_i \cdot \cos\theta_i & \cos\alpha_i & d_i \cdot \sin\alpha_i \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4)$$

As example, we present the structure of vertical lathe shown in Fig. 9.

In Table 1, the Denavit-Hartenberg parameters for bed-workpiece (*O-WP*) and bed-tool (*O-T*) kinematic branches are presented.

The transformation successive matrix for bed (O)-workpiece (*Wp*) branch are:

$$T_0^1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & a_2 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},\ T_1^2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -a_2 \\ 0 & 1 & -0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_2^{Wp} = \begin{bmatrix} 1 & 0 & 0 & a_0 \\ 0 & \cos\theta_1 & \sin\theta_1 & 0 \\ 0 & -\sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (5)$$

The transformation matrix for the attached end elements of the branch *O-Wp*:

$$T_0^{Wp} = T_0^1 T_1^2 T_2^{Wp} = \begin{bmatrix} 1 & 0 & 0 & a_0 \\ 0 & \cos\theta_1 & \sin\theta_1 & a_2 \\ 0 & -\sin\theta_1 & \cos\theta_1 & a_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (6)$$

In the same way the transformation matrix for the attached elements of the 0-*T* branch is calculated:

$$T_0^T = T_0^3 T_3^4 T_4^T = \begin{bmatrix} 1 & 0 & 0 & -a_9 + a_3 - a_6 - a_8 - s_V \\ 0 & -1 & 0 & a_5 + s_T \\ 0 & 0 & 1 & a_4 + a_7 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (7)$$

The transformation matrix between the workpiece and tool (fictitious mechanism *Wp-T*) results in the form:

$$T_{Wp}{}^{T} = (T_0{}^{Wp})^{-1}\ T_0{}^{T} \quad (8)$$

On the basis of relation (5), the coordinates (x_{Wp}, y_{Wp}, z_{Wp}) of a point in the workpiece reference system result. As well, one can obtain the coordinates (x_T, y_T, z_T) for a point in the tool reference system. In both cases, one knows the point coordinates in the bed reference system (x_0, y_0, z_0). These have the form:

$$\begin{cases} x_{Wp} = x_0 + a_0 \\ y_{Wp} = y_0 \cos\theta_1 + z_0 \sin\theta_1 + a_2 \\ z_{Wp} = -y_0 \sin\theta_1 + z_0 \cos\theta_1 + a_1 \end{cases};$$

$$\begin{cases} x_T = x_0 - a_9 + a_3 - a_6 - a_8 - s_V \\ y_T = -y_0 + a_5 + s_T \\ z_T = a_4 + a_7 + z_0 \end{cases}. \quad (9)$$

Subtracting the equations corresponding to the two equation systems the relations between the inputs and outputs of the workpiece-tool fictitious mechanism result:

$$\begin{cases} x_{Wp} = x_T + a_0 + a_{01} + a_9 - a_3 + a_6 + a_8 + s_V \\ y_{Wp} = (a_5 + s_T - y_T)\cos\theta_1 + (z_T - a_4 - a_7)\sin\theta_1 + a_2 \\ z_{Wp} = (y_T - a_5 - s_T)\sin\theta_1 + (z_T - a_4 - a_7)\cos\theta_1 + a_1 \end{cases}. \quad (10)$$

Equation (7) expresses the parametric equation of the generated path through the fictitious mechanism *Wp-T*.

Application. For simultaneous motions with constant speeds w_X, w_Z and ω corresponding to the CNC axes *X*, *Z* and *C* the equations of a conical helix are obtained based on eq. (9):

$$\begin{cases} x_T = w_Z t \\ y_T = w_X t \\ \theta_1 = \omega t \end{cases},\ \begin{cases} x_{Wp} = w_Z t + a_0 + a_{01} + a_9 + a_8 + a_6 - a_3 + s_V \\ y_{Wp} = (a_5 + s_T - w_X t)\cos\omega t + (z_T - a_4 - a_7)\sin\omega t + a_2 \\ z_{Wp} = (w_X t - a_5 + s_T)\sin\omega t + (z_T - a_4 - a_7)\cos\omega t + a_1 \end{cases}. \quad (11)$$

If $w_X = 0$ the equations of a cylindrical helix with constant pitch is obtained, and also for $w_Z = 0$ an Archimedean spiral.

For the studied case, the presented method has a general feature and is utile for interpolation methods (linear, circular, etc.) in case of generation of analytical or non-analytical generatrix *D* and directrix *G* curves.

In case of linear interpolation (G01), from the interpolated line equation ($ax + by + cz = 0$) it results

$$aw_X + bw_Z = 0 \text{ or } \frac{w_Z}{w_X} = -\frac{a}{b} = \tan\alpha = \text{const}. \quad (12)$$

For the circular interpolation (G02, G03), from the interpolated circle equation $(x - x_0)^2 + (z - z_0)^2 = R^2_{Wp}$, where ($x_0$, y_0) are the centre coordinates and R_{Wp} the piece radius, it results:

$$(x - x_0)\cdot w_x + (z - z_0)\cdot w_z = 0, \text{ or } \frac{w_z}{w_x} = \frac{x - x_0}{z - z_0}. \quad (13)$$

The linear interpolator has to maintain a constant ration between the two speeds of the feed movements (w_X, w_Z) and the circular interpolator has to assure the variation of the same relation in various points of the interpolated circle, according to relation (13).

5. CONCLUSIONS

The paper presents a synthesis which refers to representative types of CNC horizontal and vertical turning machines that exist in machine construction industry or are technically possible to be constructed.

The extension of the structure and modularization of the lathes in comparison with other types of machine tools is determined by the technological methods that can be applied, diversity of the types, and complexity of the machined workpieces, requirements specific to the flexible fabrication.

The workpiece presents an analysis of modern CNC lathes configuration with 2–8 CNC axes. On their basis, other structures with 12–14 CNC axes can be analyzed.

The formulation Denavit-Hartenberg has been applied to a CNC vertical turning machine, being emphasized the influence of the couples from the structure to the generation of the directrix and generatrix trajectories through the fictitious mechanism *Wp-T*.

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