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Aspects of kinematic structure, configuration and working possibilities of milling machining centers

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Abstract: *Taking into consideration the diversity of existing machining centers, the analysis in our paper is based on the following criteria: the functional and constructive characteristics, the kinematic structure, the placement and capacity of the tool magazine, the performance of the driving and command system, the modularization level. Significant data are presented, referring to the configuration of the kinematic chains, the number of axes numerically controlled, the type of the base machine tool, the manufacturing possibilities. The schematic representations use symbols and notations which are attributed to the structure elements and to the movement of the generating components. The number of numerically controlled axes determine the number of feed/positioning kinematic chains. The synthetic data are based on the analysis of a large number of such machine tools, many of them recently manufactured.*

Keywords: *technical performance, configuration, kinematic structures, processing possibilities, CAD-CAM simulation.*

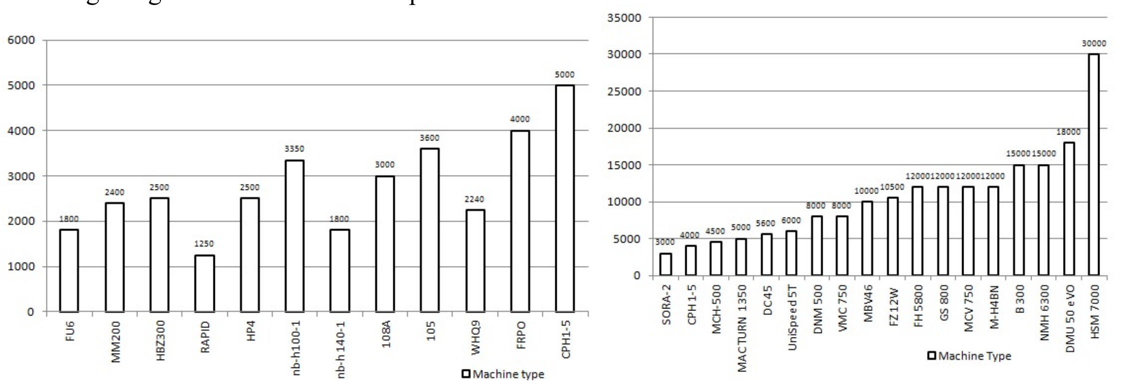
1 INTRODUCTION

Considering the main technical and functional characteristics of machining centers manufactured in different countries by different companies, their evolution over 50 years, it is important for knowing the machine tools widespread in today machines manufacturing [1], [2], [4]. These machining centers represent a technical achievement, which reflect the technological developments in machine tools and metal cutting domain [3], [6], [8]. The main advantages of using these machine tools are: short time tool change, possibility of applying a large number of technological operations in the same tool clamping, their integration in flexible manufacturing cells and systems.

These made that the rate of introducing and integrating them in industrial companies to be much greater than in the case of other numerically controlled machine tools (NCMT) [5]. The companies that produce machining centers have launched on the market numerous alternatives having architectures, kinematic structures [7] and the most diverse functional characteristics [10].

The synthetic data gathered after the analysis of several machining centers, starting with the first ones, presents the evolution of the functional characteristics: the speed range (fig. 1), speed of the feed/positioning motions, tool changing time, tool magazine capacity, kinematic structure, and configuration.

The international faire of machine tools from Chicago (1955) represented the beginning of presenting such types of machines to the attention of specialists. In the next years the first machining centers appeared in the USA [6].



a b

Fig. 1. Speed range of some machining centers: a – 1965 -1985 *;* b – after 1985.

Over time, it was established that this type of machine tool comes from the conventional machine with numeric control, to which the tools magazines and transfer mechanisms were added.

Control systems allow the tool change between main spindle and the changing point of the magazine in automatic cycle.

Regarding the evolution of NCMT, the presence of three generations is considered:

The first generation was that of the conventional machine tools, adapted to receive numerical program control system. This was made in a few steps: improving the constructive solutions; transducers used in reaction loops; using DC motors, electro-hydraulic systems or stepper motors in the feed/positioning kinematic chains. Thus, positioning speeds of 1000...1500 mm/min were possible.

The second generation was formed of machine tools designed in terms of constructive, kinematics and driving, to be numerically controlled. Structural elements were designed to be more rigid for taking over the loads in the cutting process related to parameters with higher values. Also, the demand for large and heavy machine tools have increased.

Positioning speed increased up to 5000…6000 mm/min, some machine tools being equipped with a turret head. A large increase in machining productivity was obtained.

Using CNC represents an important stage of controlling the NCMT. Also, the programming possibilities [5] of the coordinates have increased, and also the precision of the trajectory.

The third generation of NCMT and their equipment offer an increasing machining center performance. The technological possibilities have expanded, because the machining of surfaces has become increasingly complex and demands for productivity have increased.

Also, the geometric, kinematic, dynamic and thermal behaviour accuracy of machining have been improved. Because all these, significant improvement of the technological precision of machined parts is resulting [3], [6].

2 TECHNICAL PERFORMANCE OF MACHINING CENTERS

2.1. Some technical characteristics of machining centers from the second generation

The analysis made on machining centers manufactured between 1972 and 1985 shows a continuous improvement of their technical characteristics. This analysis includes also the machining centers manufactured in machine tool enterprises from Romania (Bucharest, Bacau and Oradea) [10].

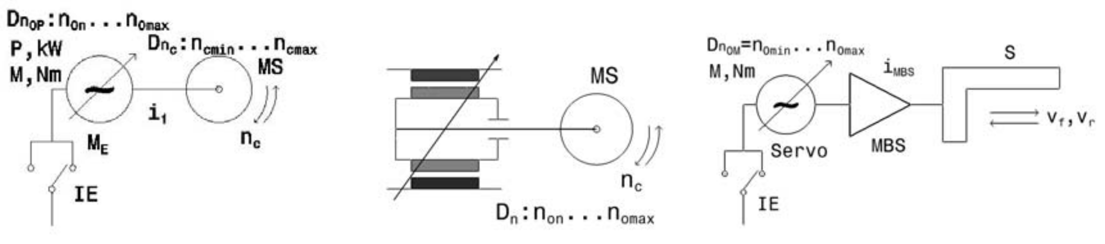
The data analysis refers mainly to the kinematic structure.

The main kinematic chain contains: AC electric motor with single speed and a gear box up to 18 steps speed. Other variants used a DC electric motor and gearbox with two, three or four speed steps.

Maximum speed of main spindle did not exceeded n_{cmax} = 3500 … 5000 rpm (Fig. 1,a). Power of main electric motor is between 5 and 37 kW, usually being below 20 kW. Feed/ positioning kinematic chains ensure speeds between 4000 and 10000 mm/min.

Figs. 2,a, b and c show some main kinematic chain structures of some machining centers [1]. Thus, we can emphasize that:

The disc or oval tool magazine is capable of storing up to 50 tools.



a b c

Fig. 2. Kinematic chains structures:a − main kinematic chain driven by an AC electric motor; *b.* integrated main spindle, *c* − feed / positioning kinematic chains structure driven by DC electric motor;

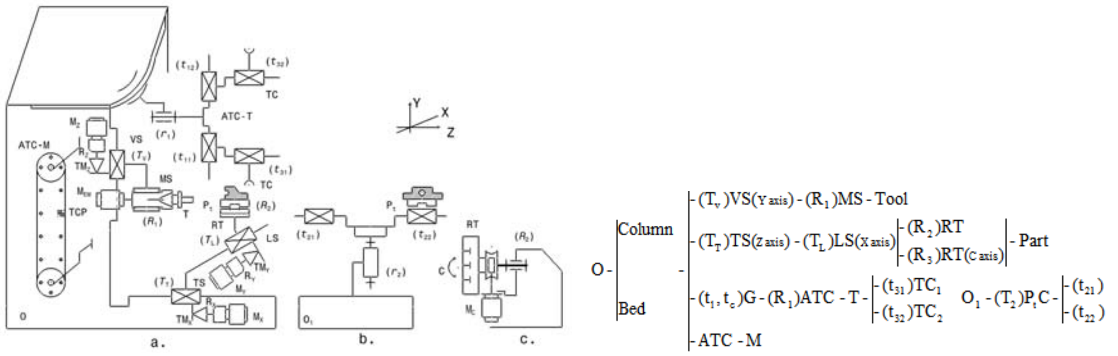


Fig. 3 Horizontal machine center CPH-500 with three CNC axes: a-*structural configuration;* b- *pallet changer;* c- *rotary table.*

The tool change time "chip to chip" was between 10 s and 20 s, which influences the maintaining of unproductive times at high levels.

In fig. 3 the kinematic structure for CPH-500-Bacău is represented.

The machine-tools, by their kinematics structure, execute simple and precise movements (rotation R, translation T) in relation to the numerically controlled axes. The correct assessment of these axes is imposed by standards and recommendations.

2.2. Some technical characteristics of machining centers from the actual generation

Modern machining centers have at least 5 numerically controlled axes: *X*, *Y*, and *Z* for translation and three rotary motions, two marked *A* and *C* for the tool, and one for the part (rotary table), the axis *B*, which is adapted on the machine as a modular assembly [10].

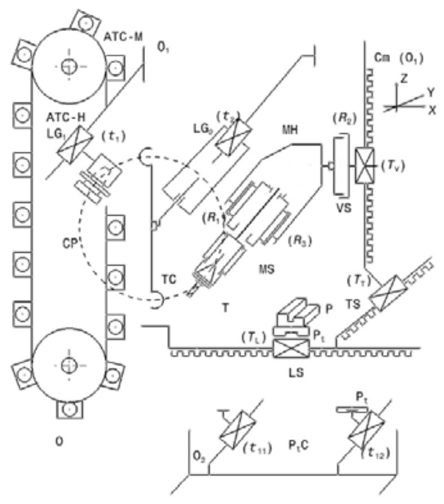
The main kinematic chain contains an AC electric motor with adjustable speed, and most of them have an integrated main spindle. The necessity of increasing the speed (n_{cmax} up to 40000 rpm) determine significant improvements of the electric motors characteristics and of the constructive solutions regarding bearings, dynamic and thermal behaviour.

On the actual CNC equipments the user may program, in addition to coordinates, other geometrical information regarding the compensation of tool wear.

Thus, it is possible to make various corrections on: the dimensions, the wear of the cutting edge, the amount of deformations, the level of tool's vibrations, and of the vibrations appeared in the fixture devices clamping the part on the machine-tool etc.

Feed/positioning kinematic chains ensures reaching a higher feed rate, 30000 … 50000 mm/min. Starting and stopping accelerations reach 2 to 3 g.

In case of higher speeds, the rotary electric motor is replaced by a linear electric motor, eliminating the ball screw mechanism (fig. 4).



O - | -(T_L)LS(X axis) - P_t - P
| - (T_T)TS(Y axis) - C_m - (T_V)VS(Z axis) - (R2)MH(C axis) - | - (R_1)MS - T ; - (R_3)MS(Baxis) - T
| - ATC - M

O_1 - ATC - T | (t_1) G_1 ; (t_2)G_2 - TC O_2 - | - (t_{11}) ; - (t_{12}) - P_t AP_tC

Fig.4 . Configuration of a MCH with three axes and palletizing system.

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The possibilities of programming cycles have been developed considerably, firmware, parameterized sub-programs for different holes, slots and cavities and sculptured surfaces.

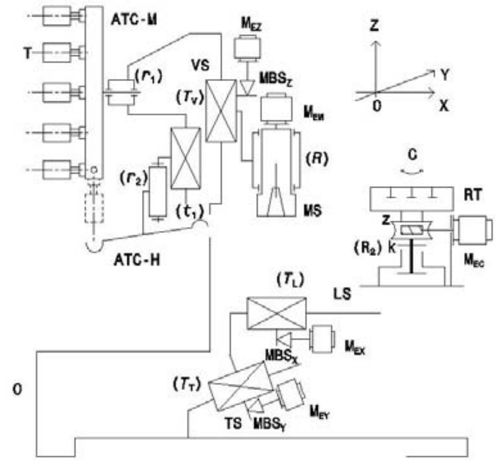
Avoiding the tool-part collisions is done by using specialized software for cutting simulation. Also, the machines allow manual programming and also the use of a CAM module for automatic generation of the codes.

Machining centers are equipped with monitoring systems for tool wear, shocks and vibration amplitude detection.

In fig. 5 the kinematic configuration of a vertical machining center (MCV) with three axes is shown. The speed range is D_{nc}: 120…8000 rpm, and the feed/ positioning one is D_{vf}: 1…10000 mm/min, positioning speed (*X*, *Y*, *Z*) is 18000 mm/min.

The generating and positioning movements are provided by the rotations couplings (R and r) and the translation ones (T and t). Also, kinematic chains structures are represented. The machine could be provided with a rotary table having a numerically controlled motion about C-axis or the axis A, B depending on its orientation.

Fig. 6 shows a configuration of a MCV with five axes that is characterized through high rigidity and increased accuracy, extended



$$O - \left| \begin{array}{l} - \left| \begin{array}{l} (T_T)TS - (T_L)LS(X\,axis) \left| \begin{array}{l} (R_2)Rt(C\,axis) \\ P \end{array} \right. \\ (T_V)VS(Zaxis) - (R)MS - T \end{array} \right. \\ - \left| \begin{array}{l} (r_1)ATC - M \\ (t_1)(r_2) - ATC - H \end{array} \right. \end{array} \right.$$

Fig. 5. Configuration of a MCV with three axes

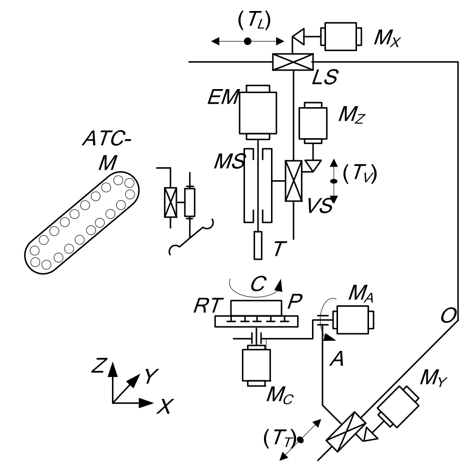


Fig. 6 . Configuration of a MCV with five axes

workspace, reduced working times, and high functional characteristics (D_{nc}: 50…20000 rpm, D_{vf}: 1…40000 mm/min, positioning accuracy of 1 μm, positioning repeatability 0.2 μm).

3.2 CAD-CAM simulation

The axes of coordinates are assigned to couples of translation and rotation of the machine. The trajectories that define the generated surfaces result from the combination of two, three or more simple movements, with determined speeds.

For demonstrating the possibilities of surface generation in proper cutting conditions, we propose a case study on a machine-tool of vertical processing center (MCV) type, 5-axis (3 translations and 2 rotations) numerically controlled (fig. 6). The CAM processes on the machine-tool are simulated in the CATIA v5 [9] working environment, along with the cutting tools, tool holders, and necessary fixture devices.

The process parameters consist of the cutting regimes, the tool paths in the processing movements, etc.

By simulation, it is possible to analyze the generation of the part surfaces based on different strategies of dividing the material excess left for machining.

The *X*, *Y* and *Z* axes assure movements for feed and/or positioning on the longitudinal (LS), transversal (TS) and vertical (VS) directions. The TS slide has a tilting rotary table

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having independent rotation motions on the *A* and *C* axes. The cutting tool T is fixed in the main spindle MS, component of the mobile assembly VS.

The part has a prismatic form and it is provided with cavities and prominences. These surfaces can be processed by simulation in the CATIA v5 CAM environment after an analysis in terms of shape, size and disposing, so it is decided to use a 5-axis MCV.

Choosing of the machine-tool having the tilting rotary table was determined by the numerically controlled axes number and orientations, the stroke lengths, the diameter of the rotary table, the range of the spindle speeds, of the feed speeds, of the quick motions, the dimensions of the working space, etc. It is recommended that, during the processing, the tool rotation axis at any point of the machined surface to be perpendicular to the tangent to the generated trajectory. This imposes the orientation of the machining surface according to the tool axis.

The chosen machine-tool has the following technical characteristics: spindle speed max.: 15 000 rpm, power of the main electric drive: P_n = 12 kW, the torque M_c = 53 Nm, machining feedrate max.: 6000 mm/min and rapid feedrate: 30000 mm/min, NC system: Sinumerik 840.

The cutting tools are provided with ISO P20 inserts (Coromant Catalogue steel milling grades). The user can determine the main features/code for each tool: diameter and length of the active part, total length, diameter and shape of the toolholder, number of teeth, the tool type for the corresponding surface shape and for the applied technological process etc.

Successively, the following processing sequence is used: face milling, in one pass, external contour profile milling, in four passes on the depth of the excess material, external contour profile and cavities semi finish milling (fig. 7), strategy *Back* and *Forth*. For the finishing milling process, it is used the *Zig-Zag* strategy, in 5 axes, on two directions (fig. 8). The first direction is on the *Y* axis and the second on the *X* axis, with repositioning between two consecutive paths.

The initial and simulated cutting process parameters regarding finish milling are given in Table 1.

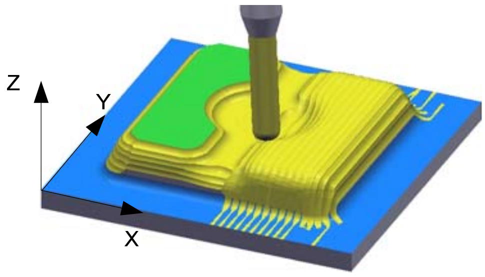

Fig. 7. Semi finish milling

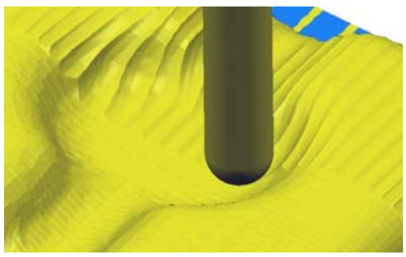

Fig. 8. Detail of the finish milling

Table 1. Processings and process parameters

No.	Name of the technological process	Cutting tool	Process parameters*	Duration, min	
				t_m	t_t
1	External contour profile and cavities semi finish milling	Ball nose end mill with 2 teeth, CoroMill 216/P, GC 2040, Main inserts E-M	D_3 = 10, r_2 = 0.3, l_2 = 160, a_p = 3, a_e = 4, hex = 0.05, f_z = 0.05, v_c = 180, n_c = 6250, v_f = 625, P_c = 0.5, M_c = 0.8, Q = 8	12.45	12.54
2	External contour profile and cavities finish milling, X axis, repositioning on Y axis	Ball nose end mill with 2 teeth, CoroMill 216/P, GC 2040, Main inserts E-M	Variant II: D_3 = 10, a_p = 0.2, ae = 2, hex = 0.015, f_z = 0.015, v_c = 125, n_c = 14000, v_f = 420, P_c = 0.3	21.2	21.67

D_3 *(mm) – tool diameter,* D_c *(mm) – cutting diameter,* l_2 *(mm) – tool length,* ap *(mm) – cutting depth,* a_e *(mm) – working engagement,* h_{ex} *(mm) - chip thickness,* f_z *(mm) – feed per cutting edge (mm),* v_c *(m/min) - cutting speed,* n_c *(rot/min) - spindle speed,* v_f *(mm/min) - feed speed,* P_c *(kW) - cutting power for removal of chips,* M_c *(Nm) - cutting torque, Q (cm^3/min) – metal removal rate,* t_m *(min) – machining time,* t_t *(min) – total time.*

4. CONCLUSION

Functional characteristics and kinematic structure are presented to show that these types of machine tools have evolved in terms of rigidity, architecture, driving and controls, axis precision, and particularly the generating and positioning movement speed.

Numerical control equipment acquired new functions specific to high speed cutting, such as: offset error range, acceleration and deceleration control before interpolation, automatic deceleration for parts provided with corners, preparing in advance the execution. It also facilitates further dialogue with the human operator, simplifying his activity.

Kinematic structures presented by cinematic couplings highlight the diversity of these types of CNC machine tools related to basic machine tools, position of the main shaft axis, layout, form and structure of the ATC.

Generating and auxiliary kinematic chains are made in modern versions: rotary electric motors and linear electric motors with adjustable speed, power and torque characteristics required to perform high speed machining, integrated spindle drive, the translation coupling rigidity.

Using the CAM simulation methodology is an important step necessary to the creation of virtual machine-tools (structural configuration, working space, collision avoidance, etc.) and to further simulations on this machine. The items which require further development are: tool path generation, control of simultaneous cutting, selection of proper machining method, tool posture control, post processing. The ultimate goal of CAM software is to generate the NC program directly from CAD data. Attempts are also being made to machine sculptured surfaces directly from CAD data by introducing a concept of digital copy milling.

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