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THE EVOLUTION AND TECHNICAL PERFORMANCES OF MACHINING CENTRES

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Abstract: *The diversity of machining centres determined that the analysis in the paper be made based on more criteria: the functional and technical characteristics, the kinematic structure, the placement and capacity of the tool magazine, the performance of the driving and command system, the modulation degree. Significant date are presented, referring to the configuration of the kinematic chains, the number of axes numerically controlled, the technical performances, the type of the base machine tool, the manufacturing possibilities. The schematic representations use symbols and notation which are attributed to the structure elements and to the movement generating components. The number of axes numerically controlled determines 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 which recently manufactured.*

Key words: *elements and components, configuration, kinematic structures, technical performances.*

1. INTRODUCTION

The main advantages of using these machine tools are: time shortage for changing the tool, the possibility of applying a large number of technological procedures in the same tool chucking, the adaptation in flexible manufacturing cells and systems.

These made that the rhythm of introducing and integrating them in industrial firms is much greater than in the case of other numerically controlled machine tools (NCMT). The firms producing machining centres have launched on the market numerous alternatives having architectures, kinematic structures and functional characteristics of the most diverse [10].

The synthetic data gathered after the analysis of several machining centres, starting with the first ones that appeared, presents the evolution of the functional characteristics: the domain of the cutting speed, the speed of the feed/positioning movements, the time of the tool changing, the capacity of the tool magazine, the kinematic structure, and the configuration.

The numeric control for machine tools appeared in 1946, from the necessity of machining complex surfaces [1, 7] at precision parts, difficult to achieve on the machine tools of that time, cam profile, moulds, rotors with palettes, carcasses, shafts etc.

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 year 1958, the first machining centres appeared in the USA. A year later the first machining centre from Germany is made, followed by other countries [2, 5, 6].

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

Control systems make the tool change between main shaft and the changing point of the magazine in automat cycle.

Regarding the evolution of NCMT, the existence of 3 generations is considered:

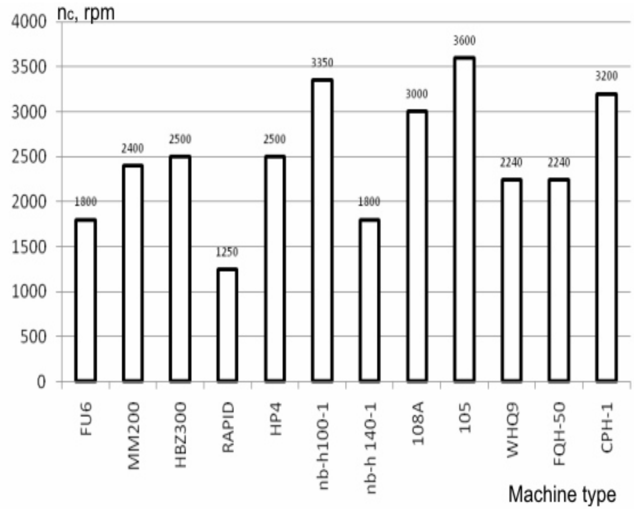
The first generation was made out of conventional machine tools, adapted to receive numeric program command system. This was made in a few steps:

- improving the rotation and translation kinematic couplings constructive solutions, the bearings, guides with intermediate elements and the screw ball mechanisms and thus replaced the sliding friction with rolling friction;
- using transducers for increasing the precision for movement measuring and for linear and angle positioning, on the reaction loop;
- using direct-current motors, electro-hydraulic systems or step-by-step motors in the feed/positioning kinematic chains.

Thus, movements positioning speeds of 1000...1500 mm/min were possible. These adaptations, modern considered did not also mean the increase of machining productivity. Also, the machining principle remained single tool – single part.

The second generation was made up of machine tools, designed in terms of constructive, kinematics and driving, to be numerically controlled, structural elements are used (beds, carcasses, columns, traverses) to be more rigid to take the loads caused by the cutting parameters with higher values. Also, has increased the requirement for large and heavy machine tools.

Speed positioning movements increased at 5 000–6 000 mm/min, some machine tools being equipped with a turret head. A large increase in machining productivity was obtained, particularly for lathes, drilling machines and milling machines. Linear and circular interpolation, fixed cycles of drilling with or without delay, deep drilling, the threading, represents the main performance of numerical control equipment and programming of such machine tools. Also, all the other elements of the technological system and technological design have been improved.



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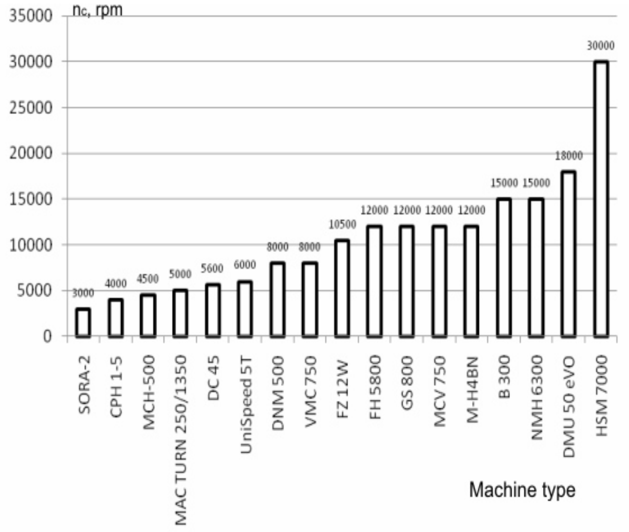


b

Fig. 1. Speed range for some machining centres.

The emergence of microprocessors in 1969, on 8 and 16 bit, and quickly placing them first in the machine tools equipment with numerical control (1970) has led to equipment CNC (Computer Numerical Control).

Using CNC represents an important stage of controlling the NCMT. Also, the programming possibilities of the coordinates have increased, thus of the contour of the part and not on the equidistance and the precision trajectory geometric calculations [9].

The third generation of NCMT and their equipment offer an increasing of the machining centres 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 of these, results significant improvement of technological precision for parts machining [8, 9].

2. TECHNICAL PERFORMANCE OF MACHINING CENTERS

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

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

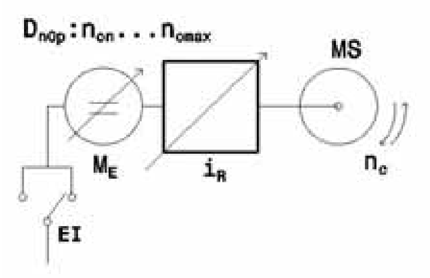
Data analysis refers mainly to kinematic structure.

The main kinematic chain contains: AC electric motor with single speed and a gear box up to 18 steps speed. Other variants have used DC electric motor and control gear with two, three or four steps speeds. Details of some variants are presented in the paper [3].

Maximum speed of main shaft has not exceeded $n_{c\max} = 3\,500–4\,000$ rpm, as shown in Fig. 1,*a*.

The power of main electric motor is between 5 and 37 kW, usually being below 20 kW.

Feed/positioning kinematic chains ensure movement speeds between 4 000 and 10 000 mm/min.



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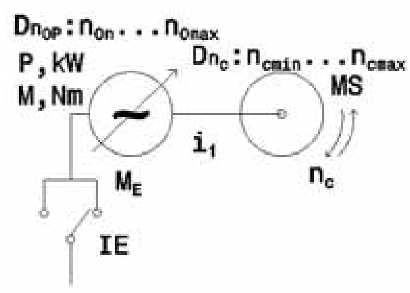

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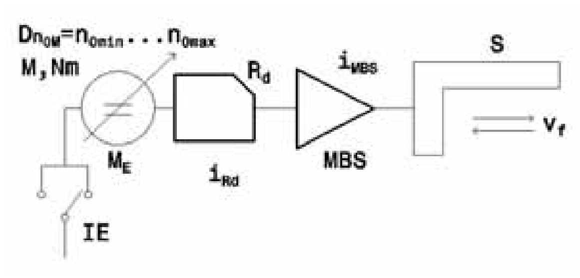


c

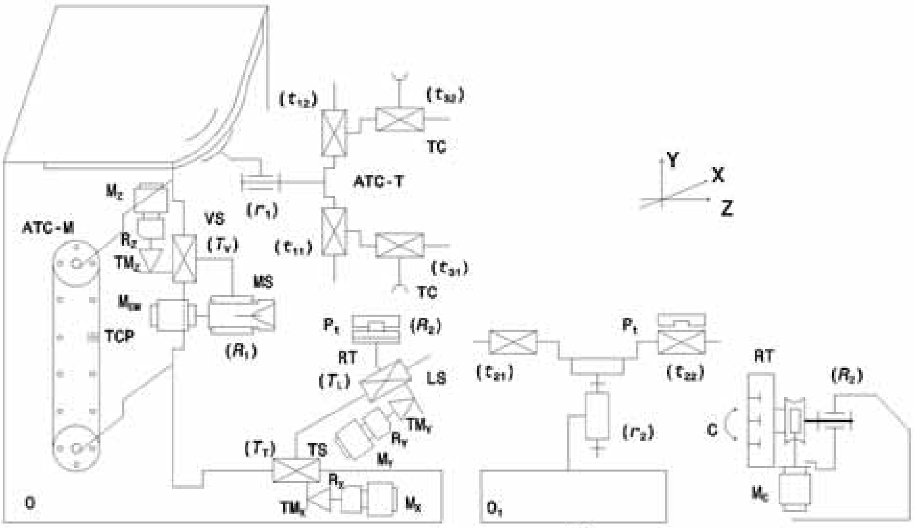
Fig. 2. Kinematic chains structures.

The representations in Fig.2 show some kinematic chains structures of many machining centres. Thus:

a. the structure of main kinematic chain is driven by DC electric motor;

b. the structure of main kinematic chain is driven by AC electric motor; (with i_1 or without intermediate mechanism (direct drive main spindle)

c. feed / positioning kinematic chains structure driven by DC electric motor.



a b c

$$
O-\left|\begin{array}{l}
-(T_V)VS(Y\,\text{axis})-(R_1)MS-T\\
-(T_T)TS(Z\,\text{axis})-(T_L)LS(X\,\text{axis})\left|\begin{array}{l}-(R_2)RT\\-(R_3)RT(C\,\text{axis})\end{array}\right|-P\\
-(t_1,t_c)G-(R_1)ATC-T-\left|\begin{array}{l}-(t_{31})TC_1\\-(t_{32})TC_2\end{array}\right.\quad O_1-(T_2)P_tC-\left|\begin{array}{l}-(t_{21})\\-(t_{22})\end{array}\right.\\
-ATC-M
\end{array}\right.
$$

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

The disc or oval tool magazine is capable of storing up to 50 tools, their encryption is made on the tool holder or on the cartridge of the tool magazine (ATC-M).

Some companies have developed machining centres with different construction forms of tool magazines [4], which reached capacity of 60 pockets. For large or heavy machining centres the maximum storage capacity is 100 pockets.

Time to change the tool "chip to chip" was between 10 and 20 s, which influence the maintenance of unproductive times at high levels. Maximum weight of the tool holder is limited to 150 N. Tool change is done with an electromechanical or hydraulic system.

In Fig. 3 is represented the kinematic structure for CPH-500-Bacau. Also in Figure 4 is represented another machining centre. The main kinematic chain has a gear box with two step speeds and DC electric motor type MCU 132. The feed / positioning kinematic chains have also servomotors (*SMU*), gear reducer (*R*), and screw ball mechanism (*MT*).

ATC contains a tool magazine (*M*) and a tool transfer system with two simple tool changers (*TC*).

The part is placed on the work table of the machining centre, directly or on palette, is rectangular, square or round, reaching maximum dimensions of 1600 × 1800 mm.

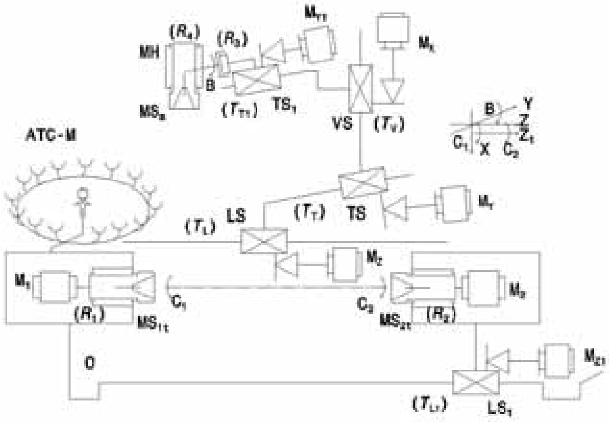
The part weight is between a few thousand of N and can reach 30000 N at large machining centres. Weight of machine is usually under 13 tF, reaching the highest weight of 33.2 tF for turning and milling processing centre, CPAF 132.

2.2. Some technical characteristics of machining centres from the present generation

The minimum number of CNC axes was 3 axes, all of translation: Z axis of rotation of main shaft, horizontal X-axis on maximum stroke of the longitudinal slide direction, and Y axis as the order to supplement trihedral I. Modern machining centres have at least 5 axes CNC: X, Y, Z for translation and three rotational motions for the part, marked A and C for the tool, and one for the part – rotary table, the axis B, adapted on the machine as a modular assembly.

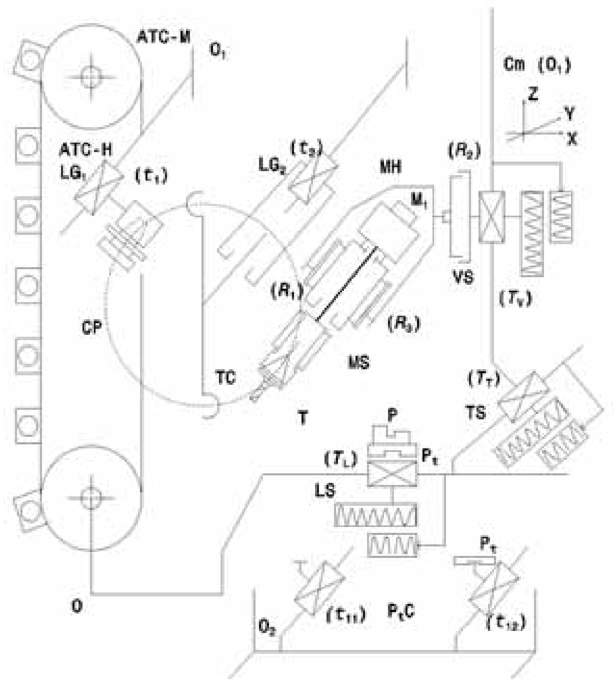
Many of the existing machining centres are based on horizontal or vertical lathes. Thus, in Figure 4 is presented to a kinematic structure indicating the existence of seven axes numerically controlled. The two main shafts are turning shafts and provide high speeds at constant power and torque.

MS$_m$ shaft is used for milling. This assembly is called milling head and can perform feed/positioning movement X, Y, Z and B axes. R_3 couplings ensure the bore axis positioning coaxial with the ATC-T in tool change position.



$$
O\left|\begin{array}{l}
-(R_1)MS_{1t}-P\\
-(T_{L1})LS_1(Z_1\,\text{axis})-(R_2)MS_{2t}\\
-ATC-M\\
-(T_L)LS(Z\,\text{axis})-(T_T)TS(Y\,\text{axis})-(T_V)VS(X\,\text{axis})-\\
\qquad -(T_{T1})TS_1(Y_1\text{axis})-(R_3)MH-(R4)MS_m-T
\end{array}\right.
$$

Fig. 4. Milling /turning centre.



$$
O-\left|\begin{array}{l}
-(T_L)LS(X\,\text{axis})-P_t-P \\
-(T_T)TS(Y\,\text{axis})-C_m-(T_V)VS(Z\,\text{axis})-(R2)MH(C\,\text{axis})- \\
\qquad\qquad\qquad\qquad -\left|\begin{array}{l}-(R_1)MS-T \\ -(R_3)MS(B\text{axis})-T\end{array}\right. \\
-ATC-M
\end{array}\right.
$$

$$
O_1-\left|ATC-T\left|\begin{array}{l}(t_1)\,G_1 \\ (t_2)G_2-TC\end{array}\right.\right. \qquad O_2-\left|\begin{array}{l}-(t_{11}) \\ -(t_{12})-P_t\end{array}\right. \qquad AP_tC
$$

Fig. 5. Horizontal machining centre with milling head and angle positioning.

The main kinematic chain contains an AC electric motor with adjustable speed, other variants have included in the electric motor case a control gear with two step speed, and most of them have an integrated main shaft. The increase of cutting speed value ($n_{c\max}$ = 40 000 rpm) has determined significant improvements of the electric motors characteristics and constructive solutions on bearings, dynamic and thermal behaviour, Fig 1,*b*.

It required the use of ceramic bearings for high speed machining, cooling and lubrication systems. The shape tool holder clamping bore of the main shaft was changed, to meet requests for inertia loading, which tend to extract the tool holder from the main shaft bore. Maximum speed of the integrated main milling shaft part of a turning machining is 10 000–15 000 rpm. Acceleration time from rest to maximum speed is 4.5 s. The power of the main electric motor (25–40 kW) must match the cutting forces and high speed cutting.

Feed/positioning kinematic chains ensures reaching a higher feed rate, 30 000–50 000 mm/min. Starting and stopping accelerations reach (2–3)g (g is gravitational acceleration, m/s^2).

Sometimes, especially over such speeds, the rotary electric motor is replaced by a linear electric motor, eliminating and ball screw mechanism.

Large tool magazine have 40–60 pockets, other machining centres are having ATC with 120 or more pockets (200 pockets). Time of tool change "chip to chip" fell below 6 s, and may go under 1 s, at small machining centres, which the time of tool holder transfer between main shaft and tools magazine is reduced to minimum. At heavy machining centres, the tool holder weight is between 12 and 30 kg.

The work table is usually square, the largest having dimensions of 1250 × 1250 mm, or round with a maximum diameter of Φ 1500 × 1850 mm. At some machine tools the work table works like a pallet, assuming a load of 70 000 N.

Pallet exchanger, adapted on the machine tool, has two pallets, while the change time of the pallet is between 10 s (for 500 × 500 mm pallet) and 50 s (for 1 250 × 1 250 mm pallet).

The electric motor that drives the work table, CNC axis, has the power 37/30 kW (operating mode 30 min / continuous operating mode).

Total weight of medium and large machining centres is between 20 and 60 tF.

Numerical control equipments have reached the sixth generation, which are equipped with 32, 64 and 128 bits microprocessors.

The possibilities of programming cycles have been developed considerably, firmware, parameterized subprograms for different holes, slots and cavities. Monitored during the use of every tool will avoid the tool-parts collisions, is diagnosed condition of tool wear, shock and vibration amplitude. Integration of personal computing is done with CNC equipment. Specific subprograms are used for high speed machining.

3. MCV 300 MACHINING CENTRE

The kinematic structure of the machine (Fig. 6) shows that it has a main kinematic chains (M_{EM}-belt drive, MS-main shaft) and three feed/positioning kinematic chains ($M_{X,Y,Z}$–$MBS_{X,Y,Z}$ $S_{L,T,V}$) corresponding to the three axes numerically controlled (*X*, *Y*, *Z*). Systems for automatic tool change (*ATC*) have two components: the tool magazine (*M*) and a mechanism used to transfer the tool (*T*).

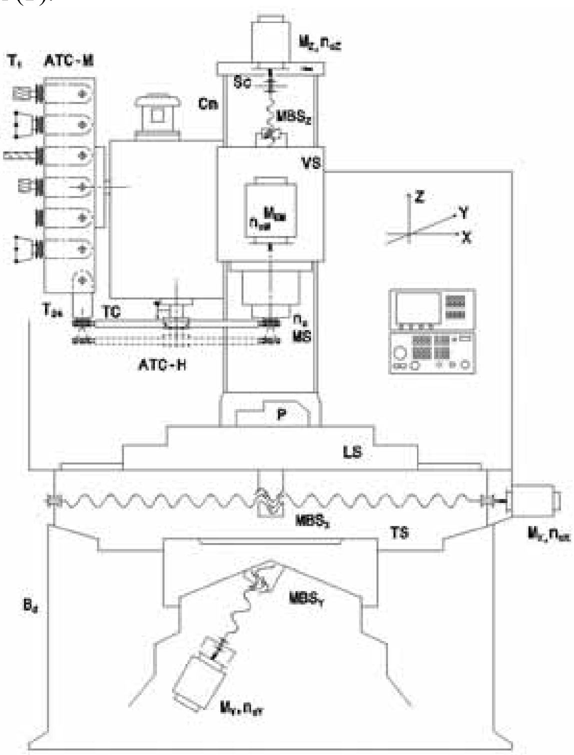


Fig. 6. Kinematic representation for MCV 300.

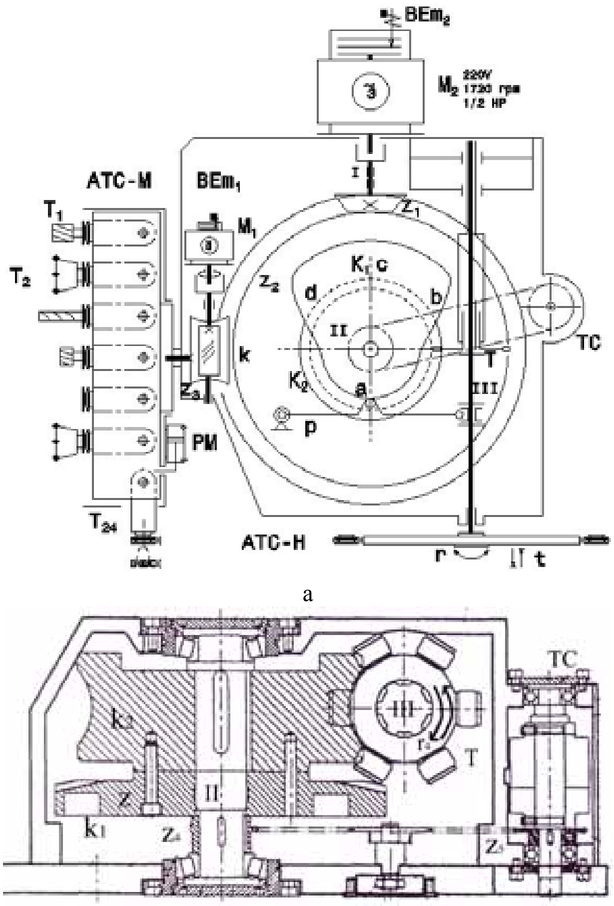
Figure 7 presents the kinematic structure and some constructive elements of the ATC system. The cutting speeds domain is D_{nc}: 120–8 000 rpm, and the feed/ positioning speeds is D_{vf}: 1–10 000 mm/min, positioning speed (X, Y, Z) is 18 000 mm/min.

The generating and positioning movements are provided by the rotations coupling (R and r) and the translation coupling (T and t). Their arrangement results from Fig. 7. Also, kinematic chains structures are represented. Machine table is positioned on the longitudinal slide LS, and one can adapt a rotary table (RT). The movement is numerically controlled by C-axis or the axes A and B.

Movement of the electric motor M_2 is transmitted to the shaft I and next by the conical gear z_1/z_2 to shaft II. On it there are two cams: disk cam k_1 and space cam k_2. k_1 cam has four angular sections, labelled a, b, c, d, and ensures translational motion (t) of the telescopic shaft III for tool change cycle through p lever. k_2 cam has two space profiles in which enter the follower cams T, through these the tool change rotation movement (r) is transmitted. The angular movement direction and speeds of shaft III are determined by two sections of the cam profile k_2.

The tool magazine rotation is controlled. The tool magazine position is provided by a kinematic chain that consists of the M_1 motor and reduction gear box with a transfer ratio k / z_3.

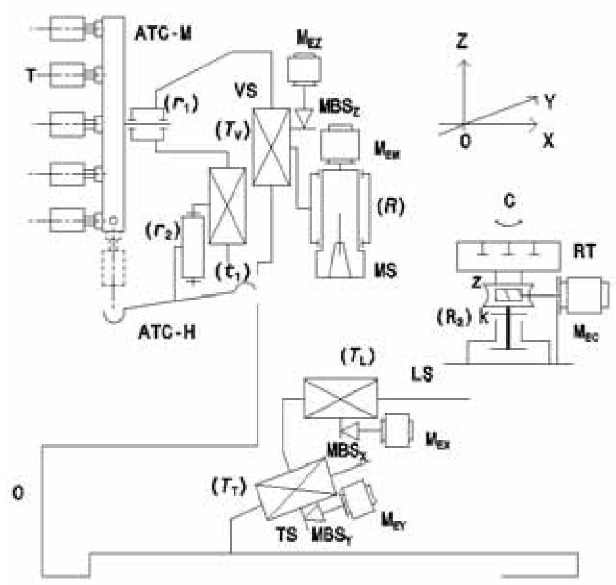
The tool change cycle is automated. Its initiation is made by a standard instruction in the command equipment. The cycle is ensured with a sequential command.



a

b

Fig. 7. Representation of ATC for MCV 300: a - kinematic representation, b - constructive solution.



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

Fig. 8. Schematic representation

4. EXAMPLES OF PROCESING

In Fig. 9 a part is presented, which is processed by milling the contour a-b-c. The groove depth on this contour is 8 mm. This represents the cutting depth a_p. A finishing end mill (SANDVIK Coromant) with radius R_T = 5 mm is used. The contour a-b-c results as a path of the tool rotation axis. The machining is made using cut-up milling.

The directory path b-c of a plane spiral (Archimedes's) has the pitch P_{HP} = constant. The kinematic equation of the trajectory is expressed by the relation

$$v_r = P_{HP} \cdot \omega_P \cdot, \qquad (1)$$

in which v_r is the radial velocity in XOY plane, and ω_P - angular velocity (C axis) in the same plane. It is considered that the next condition is fulfilled:

$$\frac{v_r}{\omega_P} = P_{HP} = \text{constant.}$$

In D point part of the directory path, tangential velocity v_d results from next components: v_r and instantaneous tangential velocity $v_t = \rho \cdot \omega_p$. The velocity ratio between v_t and v_t is:

$$\frac{v_t}{v_r} = \frac{\rho}{P} \neq \text{constant, } \rho - \text{variable.}$$

These two velocities are expresses as $v_t = n_{M\,EC} \cdot \frac{k}{z}$; and $v_r = n_{\text{MEX}} \cdot i_{MTx}$, in which n_{0M}, $n_{0\text{MEX}}$, k, z, i_{MTx}, corresponding notation from the Fig. 9. Thus, we have:

$$\frac{n_{M\,EC}}{n_{\text{MEX}}} = \frac{i_{MTx}}{\frac{k}{z}} \cdot \frac{\rho}{P} = K \cdot \rho \text{;where } K = \frac{i_{MTx} \cdot z}{k \cdot P}. \qquad (2)$$

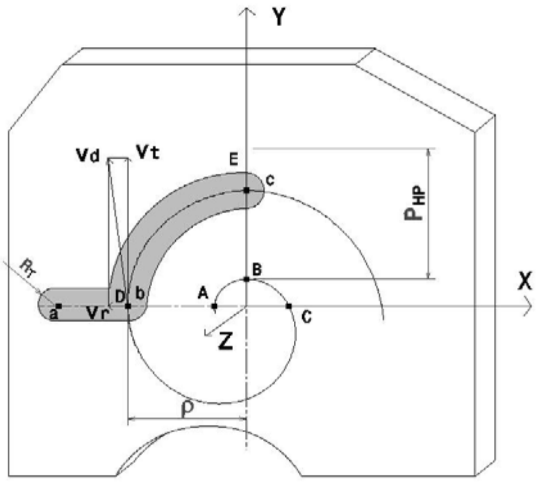


Fig. 9. Generating the trajectory.

According to relation (2) for generating cinematic directory *b-c* imposes a fraction of two speeds to match the parameter ρ on the X axis direction.

The control equipment can provide simultaneous variation of motor speed (M_{EC} and M_{EX}), or only one of these [11]. We can be consider n_{0MEX} = constant and n_{0M} variable.

The *a-b* sector of the directory curve is generated by a rectilinear directory with a particular feed/positioning speed: $v_{fab} = n_{MEX} \cdot i_{MBSX}$.

5. CONCLUSIONS

Highlighting the main technical and functional characteristics of machining centres manufactured in different countries, by different companies, their evolution over 50 years is important for knowing the machine tools with high share in today machines manufacturing. We can consider that machining centres represents a technical achievement, which highlights the technological developments in machine tools and metal cutting domain.

These machines have become more powerful, and come from NCMT conventional type as: lathes, milling machines, boring and milling machines, grinding machines, and some specialized machine tools.

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, coupling precision, and particularly the generating and positioning movement speed.

Maximum main shaft speeds increased in the last 15–20 years 3–5 times. The feed/positioning movement speed range has increased up to 5 times. Also, appeared and rapidly expanded the use of linear electric motors.

Starting and stopping accelerations exceed several times the gravity acceleration g. ATC performance have increased leading to a decrease of 3–4 times of the tool changing time. Also, it was established and imposed new performance criteria, such as: on-off acceleration, the speed coefficient, main shaft acceleration time from zero to maximum 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 for up to 10 sentences of execution.

It also facilitates further dialogue with the human operator, simplifying the activity of the programmer.

Kinematic structures presented by cinematic coupling highlights 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.

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