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TENDENCIES IN HEAVYMACHINE TOOL BUILDING

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Abstract: *Machine tool production, as any other human activity, is based, besides the personnel knowledge, on research, market requirements, information get from competitors or partners. At specialized fairs, from companies catalogues one could find which are the competitors' achievements, which are the products parameters, but very few as for the ways those performances have been obtained (know-how). In this work they will be shown aspects connected to achievements tendencies relating to the systems used at heavy machine tools providing the technical performances: output, accuracy, and technological flexibility.*

Key words: *heavy machine tools, construction, production, market, tendencies.*

1. FOREWORD

The competition among manufacturers is leading to increasing the machine tools performances, to conceiving of systems, to remove the previous or present drawbacks and problems, including the use of assemblies made by specialized companies.

Considered as the biggest initiative in the production systems area, the NEXT project [5] intends to determine the machines of the future and new business models among manufacturers and end-users, which signify an important technological, industrial and social advance in Europe, so contributing to the transformation of the manufacturing industry, faced with new challenges that arise: delocalization, low manufacturing costs in emerging economies.

2. TECHNICAL AND TECHNOLOGICAL FEATURES

Machine tool price or machining cost cut down are not always the essential or exclusive factors in machine tool designing and manufacturing. The machined surfaces quality (dimensional, shape and relative position accuracy, roughness) preservation of the machined parts features (hardness, crystalline structure etc) are directing to use more and more intensive cutting conditions (speeds, feeds) assisted by the tool makers, too, by two methods [1]:

a. High Speed Cutting (HSC) machining, reaching values higher than 300m/min for hardened steel, 700m/min for cast iron, 1000m/min for aluminum;

b. High Performance Cutting (HPC) allowing the pitch feed increase at values of 0,8-2mm/tooth, but using rather slow speeds (up to 4000rpm). The chip quantity is 2-3 times bigger that in the case of standard cutting tools. Those procedures are providing a higher machined surface quality, are requiring lower cutting power, leading to increasing the machine and tool life, they are generating lower heat in the work piece, lessening the machine time and its cost.

To apply those procedures implies several conditions:

- machine tool rigid structure and vibration absence;
- high speed and dynamic driving systems;
- work piece and cutting tool secure, rigid and accurate fastening;
- high speed data processing CNC systems;
- efficient tool cooling systems [1] and fast chips removal [3,4].

3. STRUCTURES

Any machine tool designer and manufacturer have as main, initial technical objectives:

- machining accuracy providing and its constancy throughout the working space;
- possibility of the complete and efficient machining in a single set up of parts with multiple surfaces of complex shapes, with various orientation;
- avoiding the static, dynamic and thermal deformation by providing structural, thermal and driving symmetry.

3.1. Configuration

The change of the relative position guideways – driving screw (Fig. 1) [3] allows:

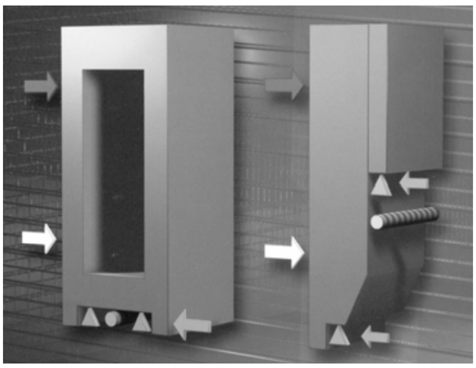


Fig. 1.

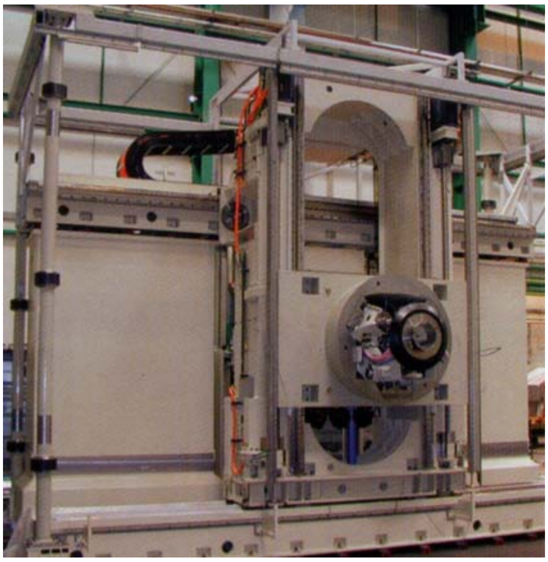


Fig. 2.

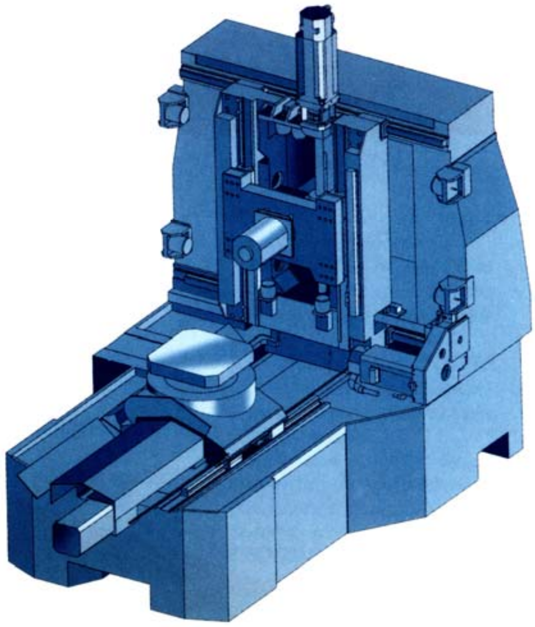


Fig. 3.

- column driving in the gravity centre neighborhood;
- weight reduction but stiffness increase;
- higher dynamic performances: acceleration (up to 0.5 g), feed (up to 50m/min).

Structure deformations both by dynamic stress and in cutting process are reduced when using box-in-box configurations (Fig. 2) [3], (Fig. 3) [7, 14]. The philosophy of those structures, used by other companies [4, 8] means to rotate by 90° the portal milling machines, of which portal is guided both at its lower and upper side. Those machines are especially used for manufacturing the large parts in aero-spatial field.

The modified machine structure implied the work piece clamping change on a vertical support. As the tool movements are rather small, but complex surfaces have to be machined, the boring spindle and the ram were replaced by a high-frequency spindle fastened on a parallel kinematic system (simplified STEWART platform) (Fig. 4) [3], driven by three independent feed mechanisms (servomotor and ball screw) and with linear rolling guideways. High – linear and angular – accelerations are reached.

A very interesting analysis of the advantages of different designs of the structures is shown in Table 1 [2].

At some heavy machine tool tables are used combinations of linear and circular movements (Fig. 5) [9, 10].

The use of machining centers and transfer lines advantages permitted to build very high output machines when machining serial production components (automotive industry, e.g.) (Fig. 6) [7].

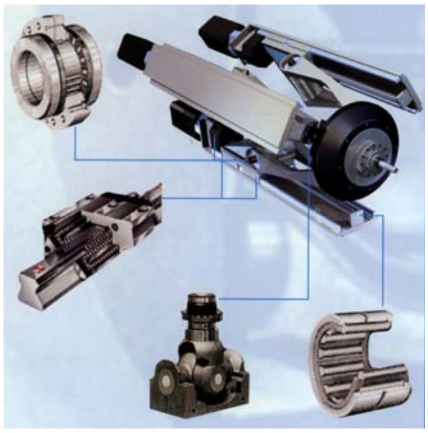


Fig. 4.

Fig. 5.

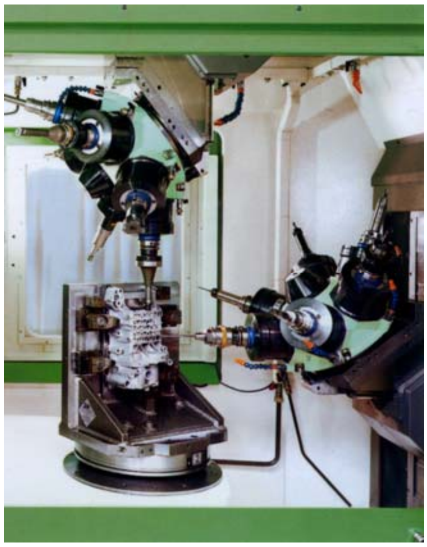
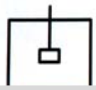
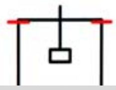
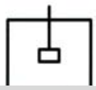


Fig. 6.

Table 1

Structure type / Parameter	 fixed portal moving table	 movable portal crossrail	 movable portal classic	 milling machines with movable column	 milling machines with movable table
Working range X axis	**4**	**5**	**5**	**5**	**1**
Working range Y axis	**5**	**5**	**5**	**1**	**1**
Working range Z axis	**5**	**5**	**4**	**5**	**3**
Machining on 5 faces	**5**	**5**	**5**	**2**	**2**
Accuracy	**5**	**5**	**4**	**4**	**5**
Dynamic behavior	**4**	**5**	**3**	**4**	**2**
Work piece weight	**3**	**5**	**5**	**5**	**1**
Accessibility	**3**	**4**	**5**	**4**	**3**
TOTAL	**34**	**39**	**36**	**30**	**18**

LEGEND: 1 – the worst .... 5 – the best

3.2. Design

The great majority of the machine tool builders are using strong ribbed structures (Figs. 7, 8) [16, 17]. Many high performance (accuracy, output) machine tools are using a structure with "high" guideways and a mobile cross rail (Fig. 9) [4]. The "high" guideways are placed on welded structures beds, filled with (cement or resin) concrete for vibration damping increase [2, 9, 13, 15].

Fig. 7.

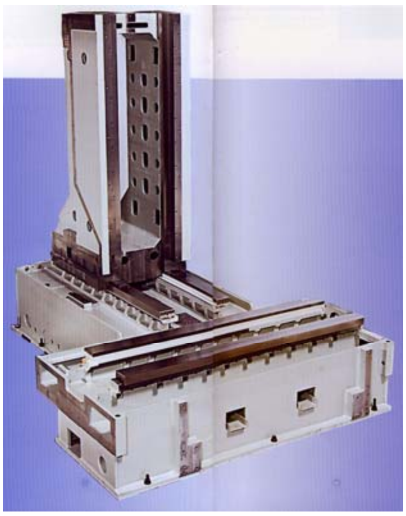


Fig. 8.

Fig. 9.

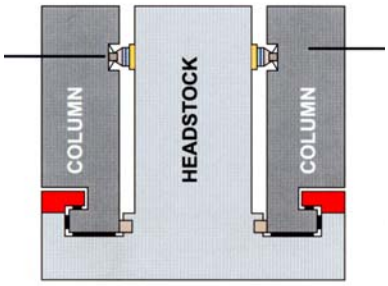


Fig. 10.

Those structures are symmetrical from thermal, driving, guiding, balancing (in the case of vertical moving) point of view. Some structures comprise all above mentioned symmetries (Fig. 10) [12], leading to high machining accuracy by providing an increased bending and torsional stiffness.

3.3. Research, simulation

The most heavy machine tool manufacturers are European, but the Asian are tacking the offensive. Within 1998-2003 the manufacturers made big investments in equipments and research, assuring a continuous modernization (rare by leaps), through the activity of R&D, technology and marketing teams, representing 10-20 % of the whole personnel [18].

The modular design of the machines permits rather easy to conform (costs, delivery term) to the customer's needs (requirements). The general tendency is to replace the horizontal boring and milling machines with portal (movable or fixed). The use of welded structures filled with concrete conducts to costs cut down and damping

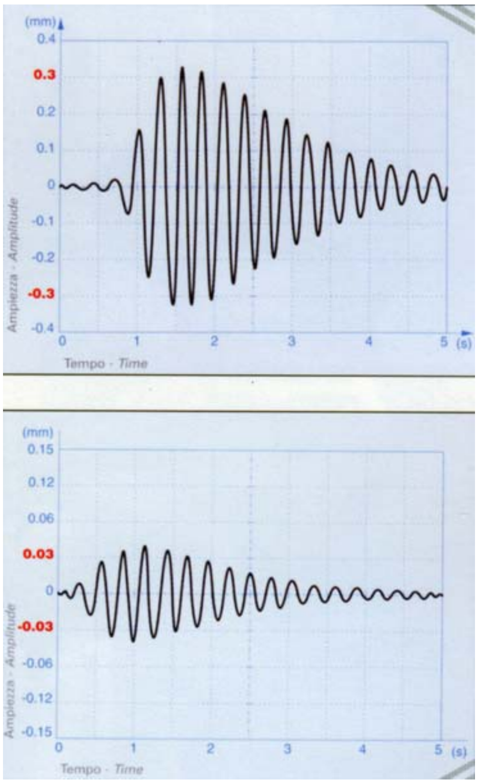


Fig. 11.

increase (Fig. 11) [15]. Machine endowment with various attachments and introduction of various measuring systems of the value of one or several parameters and their behavior, and the compensation of deviations to a reference represent fields every manufacturer is carrying on intense activities. Static, dynamic and thermal behavior simulation of machine whole structure, in various situations by FEM, checking and testing of all design versions, of the components or machine tool as a whole are ways assuring the products and companies success.

The NEXT project is a challenge for all involved in the machine tool development, manufacture and use.

4. GUIDING SYSTEMS

At the studied machine tools there are used all guideways types.

4.1. Rolling guideways

In general, they are used for moving medium size masses, with high moving speeds (sometimes over 60m/min).

In this design types they are met the following particularities:

a. it is used a large number of guiding rails (Fig. 12) [19, 24];

b. for increasing the stiffness and stability they are used 6-8 rolling blocks on each axis [23];

c. on the two guiding rails it is used a different number of rails (usually plus one on a rail) [13].

It is presumed that this arrangement would favor a better damping.

4.2. Hydraulic guideways

a. they are used on all axes, including the vertical boring and turning lathe table bearing [3], providing a peripheral speed over 40 m/s;

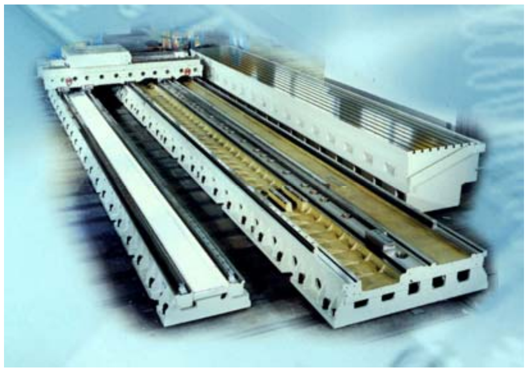


Fig. 12.

b. at the heavy machines: horizontal boring and milling machines [8, 22, 23], portal (fixed or mobile) type milling machines [4]

Their advantages are [22]:

- movement with a very low friction;
- high stiffness and a very good damping;
- practically the absence of the wear, the accuracy being kept for a long period;
- high fidelity response, a high accuracy resulting.

4.3. Mixed guideways

At horizontal boring and milling machines they are used combination of sliding guideways – lined with antifriction materials, and rolling guide ways both for relieving and side guiding (Fig. 13) [12]. The design is used at the column and table saddles.

For the ram it is used a combination of sliding guideways plated with antifriction materials and hydrostatic guideways of which pocket are built in the antifriction material (Fig. 14) [12].

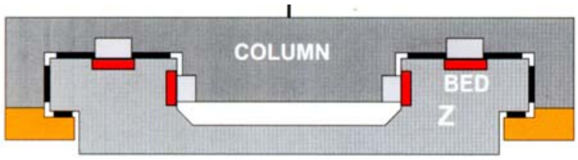


Fig. 13.

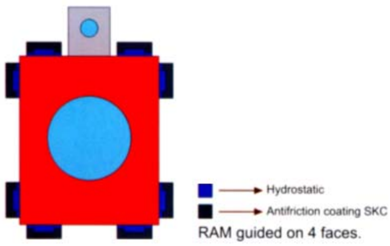


Fig. 14.

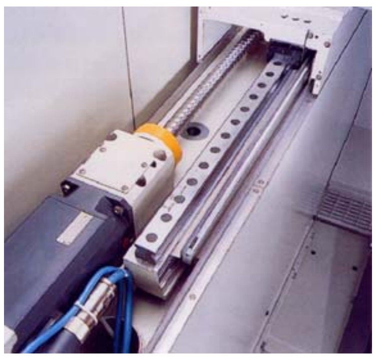


Fig. 15.

Fig. 16.

4.4. Other aspects

Same companies state explicitly, but at others it can be found from the published documents that the guiding, driving and measuring planes are very closed (Fig. 15) [15, 21, 16].

The machining accuracy of the bearing surface and the adjusted straightness of the rolling guideways is very high (0.01 mm/whole structure), to be possible to get high movement speeds (60 m/min) [15].

Due to the large variety of the materials to be machined (steel, light alloys, composite materials, carbon fibers, etc.), many feed mechanisms are sealed and pressurized for avoiding the contamination and abrasion wear [15].

5. DRIVING SYSTEMS

5.1. Main spindle driving

The general tendency is to drive the main spindles by higher and higher powers, at bigger and bigger speeds.

At the vertical boring and turning lathes:

- table driving is done by backlesh free gear boxes, both in the case of high speeds and high power [3 – BERTHIEZ];
- high peripheral speeds are reached at the table (40-42 m/s) [3, 9];
- the driving motors are asynchronous, in AC;
- the driving power could reach 100 kW and 19 kNm torque [12], or up to 150 kW [26], or even 162 kW [23] and 260 kW [9];
- milling spindle could be driven by gear boxes with 2 or 4 steps, or with the whole driving system placed in the ram [16];
- the speed range of the milling spindle endowed with boring spindles are reaching 4500-4000rpm at boring spindle diameter of 110-130 mm and over 2500 rpm at a diameter of 160 mm;
- the manufacturers are showing in their catalogues that the machine could be used at highest speed a limited period of 20-30min [4, 6, 23].

5.2. Feed driving systems

- all feed systems are driven by servomotors or linear motors, up to moving speeds of 60-120 m/min [2, 4, 6, 13, 27, 28];
- the driving motors and ball screws are over-sized for providing a high dynamics [15, 17, 28];
- movement transformation elements could be:
  - ball screws with direct drive or by means of a toothed (synchronized) belt reducer, for strokes up to 4m;
  - ball screw with driven nut by a toothed belt, for strokes up to 6m [20].

In the case of cross rail driving twin feed mechanisms are used (Gantry):

- one of the recent driving systems of long axes or of large masses (columns) consists in a master-slave system made up of two groups servomotor-reducer-pinion, with electronic control of the backlash (Fig. 16) [3, 2, 16];
- for keeping constant the operating conditions it is used:
  - the ball screw and feed motor cooling with temperature controlled water [21] or oil;
  - hydraulic preloading – constant in time – of the large ball screws [16];
- at the head stock driving it is used:
  - a symmetrical driving with two ball screws and symmetrical hydraulic balancing [3];
  - a central driving by a ball screw and hydraulic symmetrical balancing on the both sides [3].

6. BEARING SYSTEMS

They are used ever more electro-spindles, either bought or built in co-operation with specialized companies (bearings, motors). The electro-spindles are using ball bearings (often ceramic) with angular contact and lubricated, in great majority, by grease [6, 15, 16, 21, 24, 27] or with thermo-stabilized oil [20].

An interesting design [16] shows a bearing system with two taper roller bearings, the rear one (Hydro-Rib, TIMKEN) allowing the preload adjusting when running, depending on the programmed speed or the cutting conditions (through CNC equipment). A similar function is used for ceramic ball bearings [7], too.

Two designs are considered interesting to be presented:

a. EASYMILL head (Fig. 17) [4]:

- it has two main milling spindles – for roughing and finishing;

Fig. 17.

- the two spindles are alternatively operating and allow the automatic tool change;
- the milling spindles are actually electro-spindles, positioned at 90° to each other;
- the rotating axes are direct driven;

b. At the Gantry type milling machines an electro-spindle system is used, which can be automatically changed into a two rotation axes head. The electro-spindles have the same shape, dimensions and coupling possibilities into the rotation axes head, the same tool clamping system, but they have different power, torque values and speed ranges [13].

An interesting comparison between the various tool holding heads renders evident the following [3]:

- fork type milling head: it is an "open" design, with a relative low stiffness, it needs bearings, big swiveling length, high machining accuracy of the components;
- bi-rotary universal head: much stiffer than the fork type one, it has the same disadvantages of the fork type, but it can machine steel, cast iron, aluminum.

Other common disadvantages: rather slow positioning speed, big mass, low stiffness and accuracy, complicated design, asking slip rings.

- parallel architecture head (STEWART platform): it is a cylindrical head, into which various electro-spindles could be assembled, a simultaneous movement on five axes is possible (three linear and two rotary axes), it allows the automatic tool change, it is made up of standard components (from the "shelf"), assuring high speeds and feeds (linear and angular).

7. CONTROL, MONITORING, COMPENSATION SYSTEMS

At the last generation numerical control equipments it is used a PC type architecture [15, 6]. Among the possibilities they are offering they are:

a. In the case [15], using a WINDOWS operating system:

- local multitask management (work piece program, diagnosis, program transfer) or of the network;
- remote diagnosis.

At high cutting speeds the performances are optimized:

- intelligent pre-adjustable functions for optimizing the profiling accuracy and of the path speed (feed forward, jerk control, active damping);
- the look ahead function can anticipate up to 1024 blocks;
- the management of the tool tip/centre (Tool Centre Point Management);
- they are used interpolation curves (NURBS, BEZIER) assuring the path follow-up with high accuracy;
- sampling time of the closed loop and of the speed is very short – 2ms;
- it is included a software for thermal expansion of the spindle and of the errors appearing at the cutting conditions variation compensation.

b. In the case [6]:

- the program length is 4 times reduced and 17 times the adjustment period at the first work piece machining;
- cutting data library allows an automatic cutting conditions setting;
- it is carrying out learning programs, based on earlier experience;
- adaptive control of the feed depending on the main spindle loading and torques;
- accurate machining with high speeds (jerk control);
- network access at several programs;
- tool run-out detection before finishing operation (accurate machining), due to some impurities between
- the tool holder and the spindle taper bore. If the measured value is beyond the accepted one the machining is stopped.

Another way to personify (customize) the machine capabilities consists in using a CNC equipment produced by a known manufacturer (FANUC) on which it has been installed a software conceived by the machine manufacturer [27], allowing a multiple monitoring (G, M functions condition, the main spindle state, feed, tool data, main spindle, jerk control etc). The block processing time is 0.5 ms.

By combining the systems placed on the machine and the CNC equipment facilities it is possible to compensate some errors appearing when using the machine:

i. vibrations active control and damping at the tool tip up to four times [6, 16];

ii. compensation of the tool position compensation at the ram cantilever growth by tie rods, differential driving of the twin ball screws or of the hanging chains [12, 16], or supplementary, by the whole structure deforming [12, 23]. In that way the ram sag is ten times reduced (Fig. 18) [12];

iii. machine thermal deformation by [22]:

- using an oil temperature synchronizing system (from various machine systems) with the machine temperature, keeping that difference at a constant level, even if the environment temperature is changing: a constant machine accuracy is got;
- with a special option (Thermal Control System – TCS) the heat generated by the main spindle and the spindle head hydrostatic guideways is controlled;
- the boring spindle is thermo-controlled.

With those measures the main spindle moving errors (run out) are half than those allowed by the specific standards. Other systems [6] are providing an intelligent thermal protection screen (thermal distortions are controlled as function of the workshop and operating machine temperature)

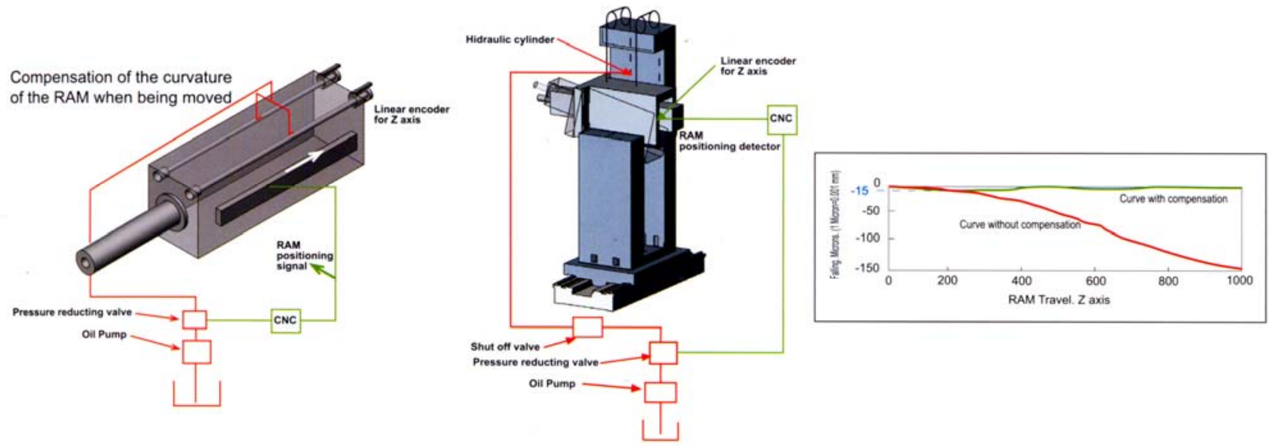


Fig. 18.

8. ACCESSORIES

For increasing the machine flexibility (technological possibilities) and complying with the principle – complete machining in a single set-up – the machine tool manufacturers are offering customers' a large variety of accessories. Those accessories could be produced by the machine tool manufacturer; they could be brought from specialized companies or built in co-operation by the two. The accessories could refer either to tools or to the work pieces.

In the case of the tools, the manufacturer could provide accessories [2] depending on:

- main spindle position;
- machining type, cutting conditions;
- machine automation level.

For work pieces, several companies offer various pallets [9] or very specialized ones [3].

Among the distinct achievements one could mention:

i. a swiveling rotary table [15, 25] (Fig. 19):

- with two rotation axes: C (360°, continuous rotation), A (–30°…+110°, swiveling), with direct drive for the both;
- the table can be endowed with independent jaws, self-centering manually or hydraulically actuated jaws.

ii. a (combined) tool support has been developed, on which various tips could be fastened, so that such a tool could replace 10 usual tools [6].

iii. a complex accessory is a movable, rotating and swiveling table (3 numerically controlled axes) (Fig. 20) [24].

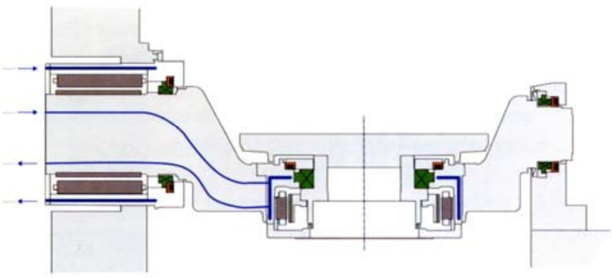


Fig. 19.

Fig. 20.

9. CHECKING METHODS

The conviction of the manufacturer himself, first of all, and then of the customer that the machine meets all the technical and security conditions etc is done by various testing (checking) methods. Those methods can be standards for some checking types (geometrical accuracy, positioning accuracy, machining accuracy, noise level etc) or according to more recent standards [29, 30].

Those methods:

- include al the checks which must be performed at the machine;
- are introducing space evaluation methods of the accuracy, tacking into account all the machine freedom degrees.

The new checking methods imply new measuring instruments (laser measuring system with new hardware and software components) and manufacturer personnel training.

10. CONCLUSIONS

Heavy machine tool manufacturers, machines which are almost all one-of-a-kind, are increasing the success chances if:

- they succeed to understand very well what the customer wants, or, maybe, more important what the customer really needs. If means a co-operation on the whole path of producing the machine, starting with both the manufacturer's and customer's experience and achievements;
- they deliver to the customer a machine with a high flexibility level, reliable and safe in use, accurate in the whole working space, with an opened architecture (which could be later developed, improved);
- those wishes could be reached by company or national policies (e.g. Taiwan) and a very close co-operation with the (hardware and software) component manufacturers.

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