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DEVELOPMENT OF MACHINE TOOL OPERATIONAL PROPERTIES

This paper presents the main directions in the development of machine tools and the practical implementations of new technologies by machine tool producers, aimed at meeting the business requirements. The possibilities of applying intelligent functions in high-performance machine tools and the trends in the development of intelligent machine tools are discussed. The vital importance of the holistic modelling and numerical simulation of the operational properties of machine tools at all the stages of their creation and the necessity of integrating the machine tool with the control system and the process during simulation and virtualization are highlighted.

1. INTRODUCTION

Most of today's machine tools are numerically controlled, perform an increasing number of machining (often hybrid) tasks, are characterized by steadily increasing machining accuracy and are increasingly environment-friendly and reliable. The great variety and complexity of machining tasks stem from the users' business requirements, but also from the very strong competition on local markets and on the global market, demanding very effective design and manufacturing. Machine tools must be highly efficient, but at the same time inexpensive. An increase in their high efficiency and high operating parameters can be achieved through the use of the most advanced design techniques (including digitization and virtualization), the techniques of identifying utilitarian operating properties, the most suitable but inexpensive construction materials and particularly efficient system and technological software systems and modules. Moreover, the development of today's machine tools is mostly based on manufacturing, business, factory and particular machine tool type (depending on its share in manufacturing) development strategies. Such a classification of the machine tools produced today is presented in Fig. 1, which shows that currently milling centres, turning centres and grinding

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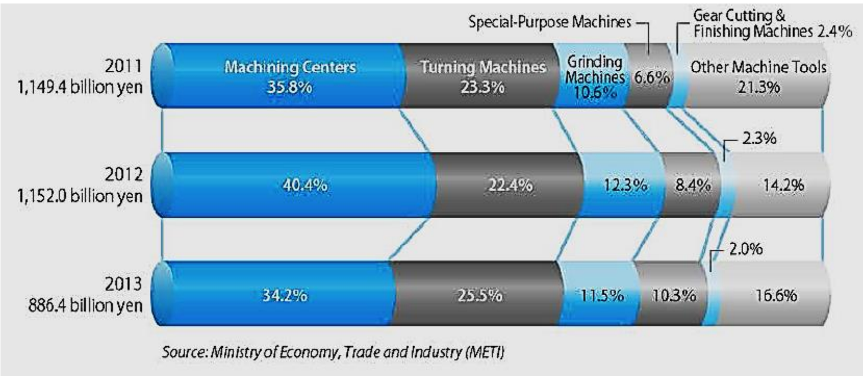
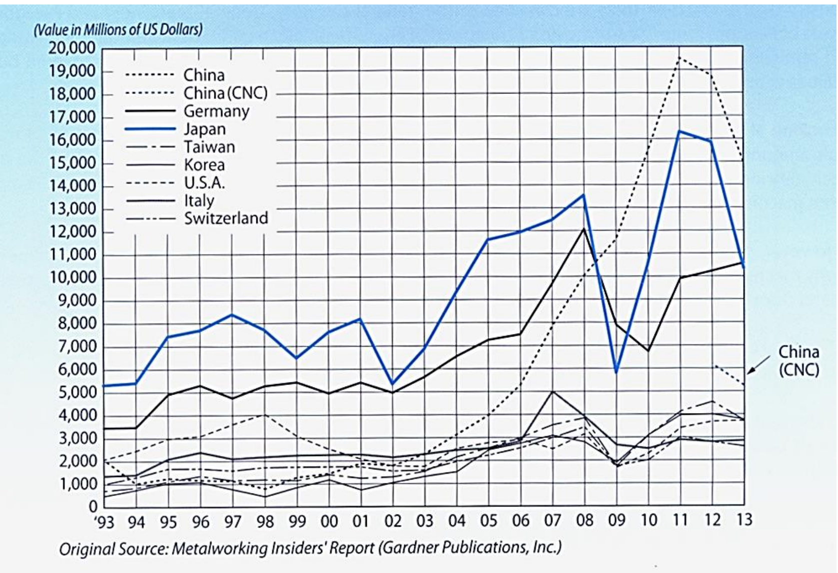
machines predominate in the manufacturing systems. Also the share of special-purpose machines is significant.



Source: Ministry of Economy, Trade and Industry (METI)

Fig. 1. Machine tool production by type of machine [26]

The steadily increasing importance of machine tools in manufacturing is well reflected by the development of production over the recent years in the countries being leaders in this production.



Original Source: Metalworking Insiders' Report (Gardner Publications, Inc.)

Fig. 2. World machine tool production (metal cutting type) [25]

The above highly condensed assessment of machine tool development indicates that its detailed and in-depth analysis is difficult. Therefore attention was focused on the aspects and directions of this development. It was assumed that the development of machine tool efficiency is inextricably linked with the implementation of intelligent functions in machine tools. Because of machine tools multitasking and technological flexibility, the growing requirements as to their static, dynamic and thermal properties (translating into machining accuracy) make it necessary to use the most efficient software tools to design machine tool structures and machining processes. The tools must be intensively developed and used already at the early design stage. Accurate modelling and numerical simulation must receive special attention. They are not only the subject of scientific improvement, but also have become commonly used in industrial practice [5],[24],[39],[43].

It is very difficult, but necessary to further increase the precision of machine tools and machining processes. Precision is expensive, but it must be achieved through inexpensive means in order to ensure cost-effective manufacturing. Hence it is continuously the subject of wide research conducted in academic centres and industrial laboratories. It is simply impossible to leave the main directions in this research and the recent practical applications stemming from it out of the discussion of the trends in the development of high-performance machine tools. The operating conditions of machine tools in which high efficiency is to be achieved are particularly difficult. They are currently characterized by high motion dynamics, increasingly higher speeds of rotational and feed motions and high accelerations and jerks. The requirements for the dynamic stability of machining processes at high machining speeds and torques, which is difficult to ensure at high machining efficiency, increase. Research must aim at the integration of the machine tool with the machining process in all the aspects of reaching high accuracy and efficiency. Also the requirements as to the accuracy achieved in the controllable axes in the operating conditions increase. The lifetime of this accuracy has a great bearing on the production costs.

In the case of multitasking and the consequent interactions, it is necessary to optimize the machine tool structure and the machining processes. Hence considerable research effort is put into the identification of loads and interactions through holistic modelling and numerical simulation and the precise identification and on-line compensation of errors. The minimization of errors in this case is key for achieving high machining precision.

Two very important problems, i.e. the improvement of machine tool service and energy intensiveness, have been omitted here since they will be the subject of a separate paper.

In papers providing an overview of the development of machine tools, the conclusions largely depend on their authors’ knowledge and views [5],[10],[35],[39].

2. DEVELOPMENT OF MACHINE TOOL INTELLIGENCE

The idea of the integration of NC machine tool and intelligent functions were put forward by Moriwaki already in 1993 [28] and recently developed by Shirase [34]. As demonstrated by D. Hanaki (Okuma Co.) in his unpublished paper delivered at the CIRP Conference HSC 2012 in Nagoja, there is a close dependence between the development of machine tools and their intelligent functions and the development of numerical control systems. This dependence is presented in Fig. 3.

The introduction of microprocessors made CNC (based on the developed software) possible. Controllers integrating IT (Pentium, Windows) and developed databases were the next step. Today the fusion of the machine tool, control, IT and intelligent functions takes place. An intelligent NC system and an intelligent machine tool are being created. Shirase considers digitization and active tool path shaping in real time (consistently with the workpiece 3D CAD in a proper format) as the basis for the development of the intelligent machine tool.

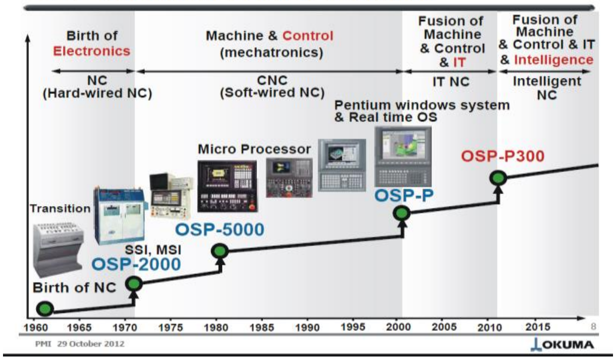


Fig. 3. Development of machine tool numerical control systems (Okuma Co.)

The advanced Machine Monitoring System, making process data acquisition possible, provides another basis. There are already several advanced monitoring systems.

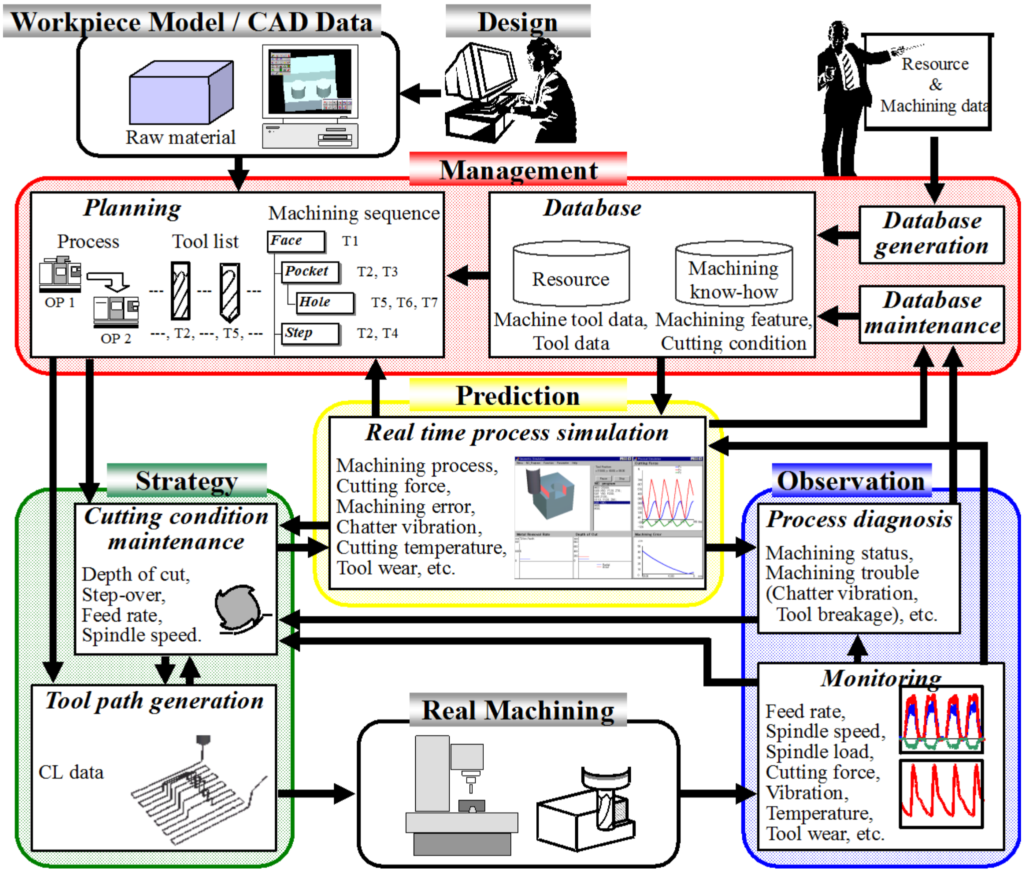


Fig. 4. Conceptual structure of Autonomous and Intelligent Machine Tool [34]

In the intelligent system (Fig. 4) one should distinguish the following modules: a workpiece model, a management module, a positioning module, a strategy module, an observation module and a real machining module. A tool path is created in real time on the basis of information about the course of the process. This is perhaps the clearest intelligent machine tool model from the ones found in the literature on the subject.

In practice there exist several ways of counteracting any disturbances to the machining process. The MAZAK Corporation lists them in its catalogues. Susuki [38] considers the following measures/devices to be intelligent:

- Active Vibration Control,
- Intelligent Thermal Shield,
- Intelligent Safety Shield,
- Voice Adviser (Verbal Message System),
- Intelligent Performance Spindle,
- Intelligent Maintenance Support,
- Intelligent Balance Analyser.

A machine tool equipped with the above measures undoubtedly has the hallmarks of intelligence, is much more efficient and productive in comparison with a machine tool which has no such disturbance reducing measures. Also many machine tools produced by other leading producers are equipped with similar measures. The anti-crash system developed and used by the OKUMA Co. (Fig. 5) is worth showing here.

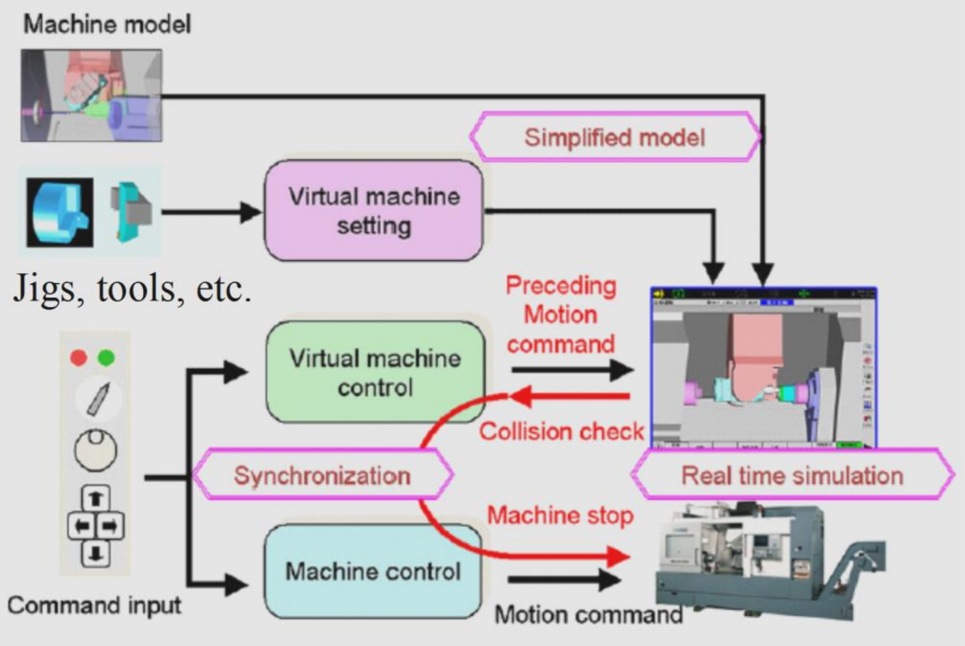


Fig. 5. Conceptual diagram of anti-crash system (Okuma Co.)

Several intelligent functions, particularly the diagnosis of machine tool behaviour [11] and the machining process supervision, were implemented in machine tools quite a long time ago. Today attempts are made at the self-diagnosis and self-supervision of the dynamic and thermal properties of the machine tool. These are improvement measures leading to increasingly greater autonomy of the machine tool. A challenge is posed by the integration of models of machine tool operational properties with cutting process models [3],[7],[18]. The mechatronic solutions aimed at this are mostly highly expensive, but in some cases indispensable [29]. It is anticipated that the future intelligent machine tools will incorporate an increasing number of intelligent materials [27],[30]. For example, the intelligent action of grease, which as the rotational speed increases, automatically releases the required amount of base oil into the friction zone to ensure proper lubrication conditions, has been known for a long time.

3. DEVELOPMENT OF MODELLING AND NUMERICAL SIMULATION

The improvement of machine tools on the basis of modelling and numerical simulation is today not only the subject of research and optimization, but also has become commonly used in the industrial practice. Modelling and simulation bring very good results in the improvement of the operational properties of machine tools at all its stages, beginning with the preliminary design.

The essence of the currently developed modelling is the holistic approach, the increasing higher accuracy and the integration of the machine tool with the cutting process, which significantly enhances the capabilities and effectiveness of identifying and minimizing disturbances and compensating errors [5],[6],[18]. Of major importance is the steadily increasing computing capability of FEM system. Great emphasis is placed on the accurate rendering of the interactions between the disturbances of machine tool static, thermal and dynamic properties, to which the holistic approach to modelling and simulation is conducive. This leads to the increasingly more precise modelling of errors in the controllable axes and creates possibilities for their more accurate compensation. As a result, also the machine tool load bearing structure is more effectively optimized and its effect on machining dimensional errors and thermal and dynamic stability is minimized [14],[31],[37]. The integration of computing systems with knowledge bases and databases (subject to continuous improvement) becomes increasingly important.

The created models and simulation systems must take into account on one hand the latest knowledge about the main machine tool assemblies (particularly the drives of the rotational and linear axes) and their designs and on the other hand, the machine tool users' growing requirements as to multitasking, torque, dynamics, precision, cost, energy consumption and service friendliness. In order to be effective machine tool improvement must increasingly accurately take into account machining process interaction, which is difficult, but brings about very good results [3]. Figure 6 shows the possibilities of integrating the machine tool with the cutting process, in the machining parameters optimization procedure, using the constraints imposed by the machine tool and the cutting process. Machining parameters, such as speeds, feed rates and depths of cut must be properly matched in order to improve the process efficiency and the end product quality. The most effective machining parameters, considering the constraints resulting from the interaction between the process and the machine tool, are determined using the proposed procedure based on a description of the physical phenomena accompanying the cutting process. The constraints include: cutting forces, chip thickness, spindle power and torque, workpiece errors and system stability. The aim of the optimization is to achieve the highest possible material removal rate (MRR).

In order to create model and software solutions applicable to many types of machine tools and processes and to predict their behaviour in real time one needs first of all holistic models and computing systems as well as very fast computations and intelligent procedures integrating IT, knowledge and the machine tool with the process proper for HSC.

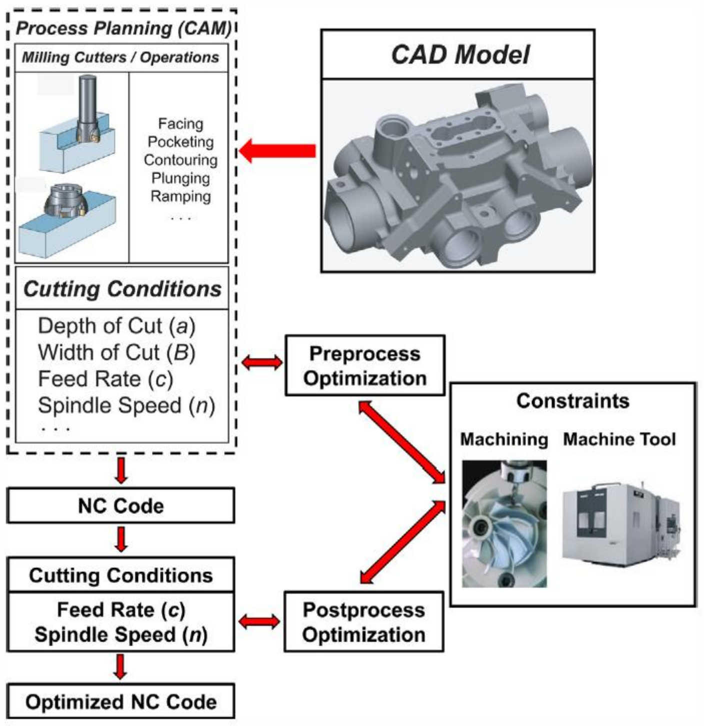


Fig. 6. Flow chart of optimization procedure [3]

The improvement of the operational properties of machine tools generally begins with the modelling and simulation of the static, thermal and dynamic properties of the load-bearing structure. At this design stage it is essential to analyze eigenfrequencies and eliminate irregularities through appropriate structural changes.

In more complex modelling and simulation the drives of the axes and NC systems are taken into account. An example here is the system developed by Fortunato [7], shown in Fig. 7. Thanks to simulation better control properties (optimization) and greater smoothness of the workpieces were ensured.

The integration of machine tool and cutting process modelling and simulation, using ANSYS, for the Heller machining centre is shown in Fig. 8 [19]. Stability charts at an increasing rotational speed of the tool, different cut layer depths and different rotational speeds of the spindle were studied for a selected cutting process. The previously determined parameters of the process and the criteria of its stability were taken into account. A significant improvement in the dynamics of the process was achieved.

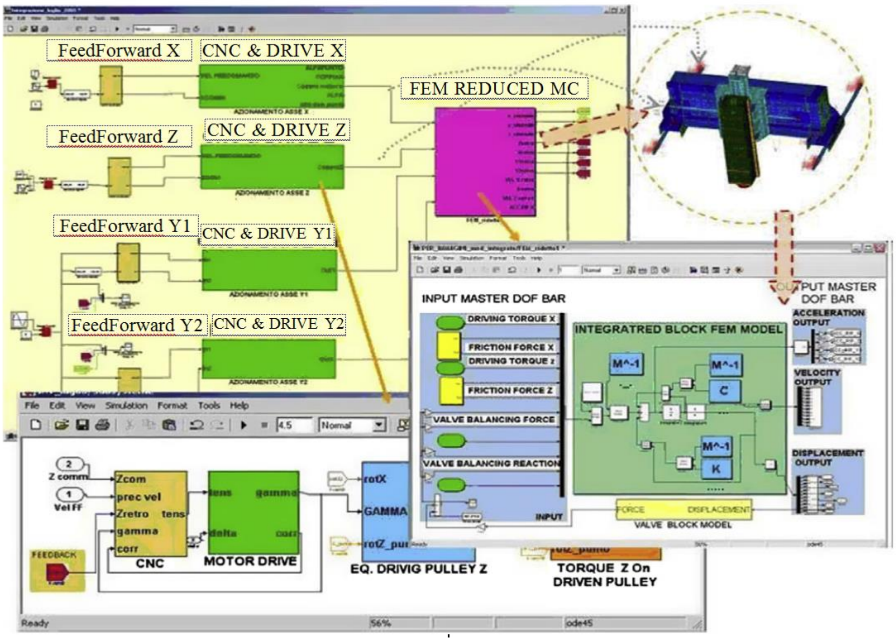


Fig. 7. Simulation system based on FEM model of machine integrated with CNC [7]

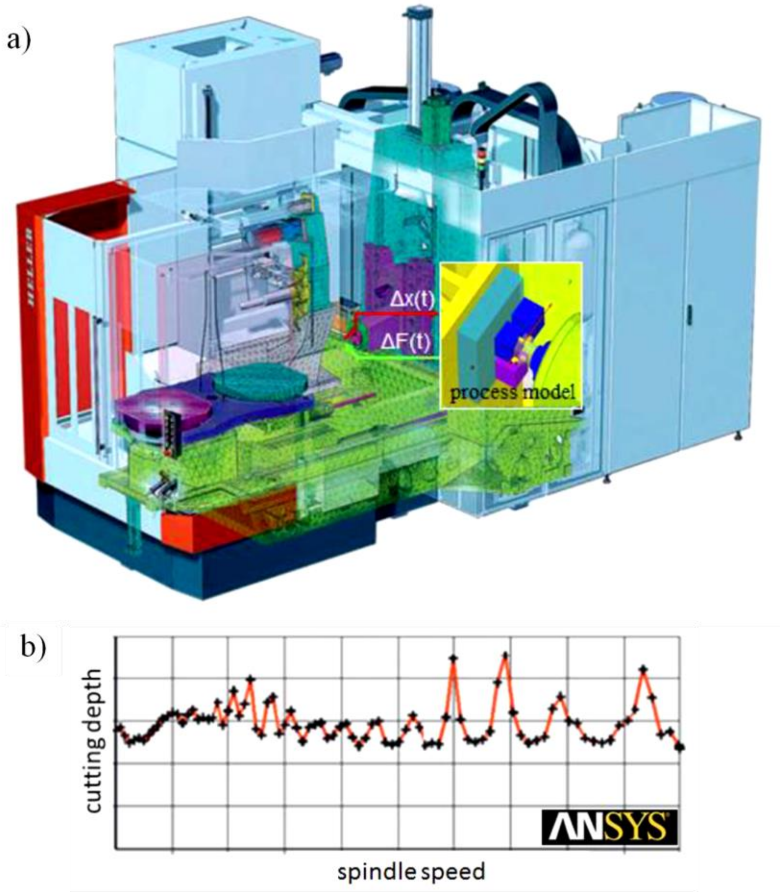


Fig. 8. FE simulation of Heller H5000 with integrated cutting process (a) and prediction of stability charts (b) [19]

The development of modelling systems increasingly tends towards holistic modelling and so towards the holistic simulation of the operational properties of machine tools. A concept of such a system, which is already being implemented, was presented by Jedrzejewski [17]. This is an in-house system for analyzing the operational properties of machine tools. It is shown in Fig. 9.

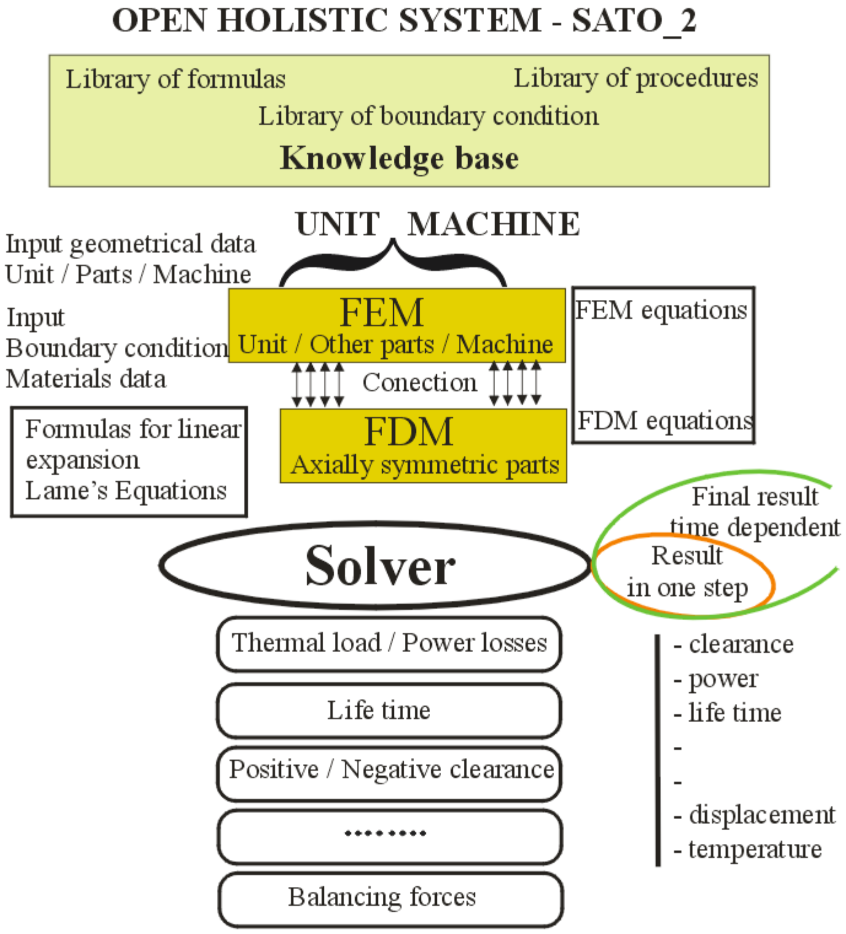


Fig. 9. Overall structure of SATO 2 system [17]

On the basis of machine tool CAD data and expert knowledge modules the system, using different software tools, integrates a set of models of the behaviour of the assemblies and the whole machine tool in the operating conditions. In its database the system has very advanced models and subsystems for the simulation of power losses, which are key for the analysis, identification and improvement of the operational properties. Owing to this, using proper solvers one can determine thermal and static loads, temperature distributions and displacements in time and 3D space, taking into account the mutual interactions. The system is expandable, able to integrate new knowledge and take into account integration with the machining process.

This selected latest research on the improvement of the modelling and numerical simulation of the operational properties of machine tools shows that a major step has been made towards the virtualization and development of their intelligent functions.

The precise identification of errors, indispensable for the verification and improvement of models of thermal and dynamic phenomena and processes taking place in machine tools, plays a vital role in the improvement of the latter. This is of crucial importance for the holistic increasing of machine tool and machining process precision.

4. DEVELOPMENT OF PRECISION

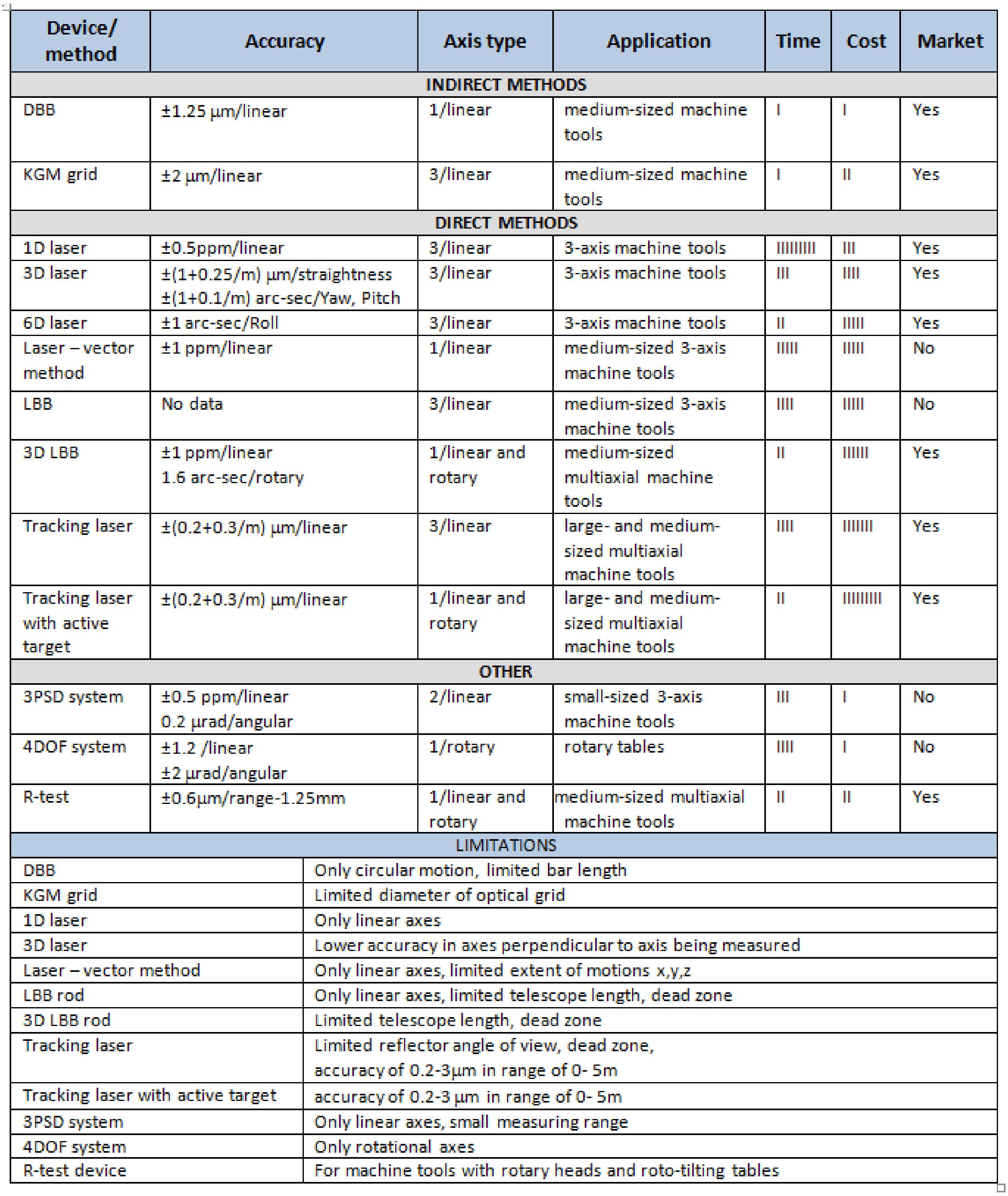
The increasing of machine tool precision is one of the main factors contributing to machining process efficiency. It consists in the accurate identification of errors and the reduction and elimination of their influence on machining precision. The total errors reflected in the workpiece can be relatively easily evaluated on the basis of machining results. The component errors, which should be individually minimized, are usually difficult to identify. Moreover, they arise partly in the machine tool, the workpiece-tool system, the production jig and in the workpiece itself. Depending on their share in the total error (in a given controllable axis), appropriate measures must be taken to reduce them. Many of the errors can be identified by means of constantly improved measuring systems/methods, mostly based on single- and multi-axis lasers. The methods are compared in table 1 [22].

They are commonly used to identify geometric errors resulting from assembly errors and thermal deformations (including the ones caused by changes in ambient temperature), and kinematic errors. Geometric errors caused by changes in ambient temperature can be identified separately and separate procedures can be created for identifying them. Many papers, e.g. [21],[32],[33], have been devoted to measuring errors. The further development of efficient methods of measuring errors is still relevant and important.

Generally, thermal errors have the largest share in machining errors. It is very difficult to prevent them in factory conditions (great skills on the part of the machine tool operator are required to do this) without support from compensation systems. Therefore the automatic compensation of the effects of thermal disturbances is needed [14],[23],[43]. The effective minimization and compensation of thermal errors should be based on an accurate model and artificial intelligence procedures, especially in the case of highly complex HSC processes. Then compensation must be integrated with the tool path in real time as the latter is being executed. So far the compensation of thermal errors, if necessary, has been conducted off-line, which is rather ineffective, or by predicting errors and introducing corrections into the path in the course of its generation. Interference into the tool path to compensate machining errors must entail a correction of the trajectory error. This means that compensation should be based on a comprehensive error model comprising all the error components which are continuously reflected in the workpiece and constitute its dimensional deviations. The effectiveness of compensation will the greater, the more error components are compensated.

The error values and the dynamics of their changes are to a large extent determined by the machine tool operating conditions, defined by the motion speeds, the accelerations and the jerk. The maximum rotational speed of machining centre spindles currently ranges from 35000rpm (OKUMA), 45000rpm (MAKINO), 42000rpm DMG MORI, 45000rpm DOOSAN to 60000rpm (MATSURA). For turning centres, the maximum rotational speed of the main and back spindles amounts to 6000-20000rpm (depending on the workpiece diameters), for milling spindles to 30000rpm and for drilling spindles to 50000rpm (TSUGAMI).

Table 1. Characteristics of measuring devices/methods used to determine volumetric error [22]



Device/ method	Accuracy	Axis type	Application	Time	Cost	Market
INDIRECT METHODS						
DBB	±1.25 µm/linear	1/linear	medium-sized machine tools	I	I	Yes
KGM grid	±2 µm/linear	3/linear	medium-sized machine tools	I	II	Yes
DIRECT METHODS						
1D laser	±0.5ppm/linear	3/linear	3-axis machine tools	IIIIIIIII	III	Yes
3D laser	±(1+0.25/m) µm/straightness ±(1+0.1/m) arc-sec/Yaw, Pitch	3/linear	3-axis machine tools	III	IIII	Yes
6D laser	±1 arc-sec/Roll	3/linear	3-axis machine tools	II	IIIII	Yes
Laser – vector method	±1 ppm/linear	1/linear	medium-sized 3-axis machine tools	IIIII	IIIII	No
LBB	No data	3/linear	medium-sized 3-axis machine tools	IIII	IIIII	No
3D LBB	±1 ppm/linear 1.6 arc-sec/rotary	1/linear and rotary	medium-sized multiaxial machine tools	II	IIIIII	Yes
Tracking laser	±(0.2+0.3/m) µm/linear	3/linear	large- and medium-sized multiaxial machine tools	IIII	IIIIIII	Yes
Tracking laser with active target	±(0.2+0.3/m) µm/linear	1/linear and rotary	large- and medium-sized multiaxial machine tools	II	IIIIIIIII	Yes
OTHER						
3PSD system	±0.5 ppm/linear 0.2 µrad/angular	2/linear	small-sized 3-axis machine tools	III	I	No
4DOF system	±1.2 /linear ±2 µrad/angular	1/rotary	rotary tables	IIII	I	No
R-test	±0.6µm/range-1.25mm	1/linear and rotary	medium-sized multiaxial machine tools	II	II	Yes

LIMITATIONS	
DBB	Only circular motion, limited bar length
KGM grid	Limited diameter of optical grid
1D laser	Only linear axes
3D laser	Lower accuracy in axes perpendicular to axis being measured
Laser – vector method	Only linear axes, limited extent of motions x,y,z
LBB rod	Only linear axes, limited telescope length, dead zone
3D LBB rod	Limited telescope length, dead zone
Tracking laser	Limited reflector angle of view, dead zone, accuracy of 0.2-3µm in range of 0- 5m
Tracking laser with active target	accuracy of 0.2-3 µm in range of 0- 5m
3PSD system	Only linear axes, small measuring range
4DOF system	Only rotational axes
R-test device	For machine tools with rotary heads and roto-tilting tables

These are already very high speeds and at the moment there is no rational basis for them to significantly increase. They are limited by the short lifetime of rolling bearings and the strong centrifugal forces acting on the rolling components of the bearings, the spindle and the spacing sleeves [13],[15]. In the developed model of the high-speed angular bearing the ball assumes the position of equilibrium for strictly specified values α_o and α_i, depending on the value of the centrifugal force (Fig. 10). The accompanying change in the contact angles of the bearings causes significant spindle shifts, which can be determined and compensated using the model (Fig. 11). The model shown in Fig. 11a is for a spindle with angular bearings mounted in the back support via a slidable sleeve tightened with springs. The internal forces in the bearings (caused by the pre-load and the centrifugal forces), determined using the model shown in Fig. 10, make the slidable sleeve with the bearings shift by Δs, whereby the spindle tip shifts by $\Delta s/2$.

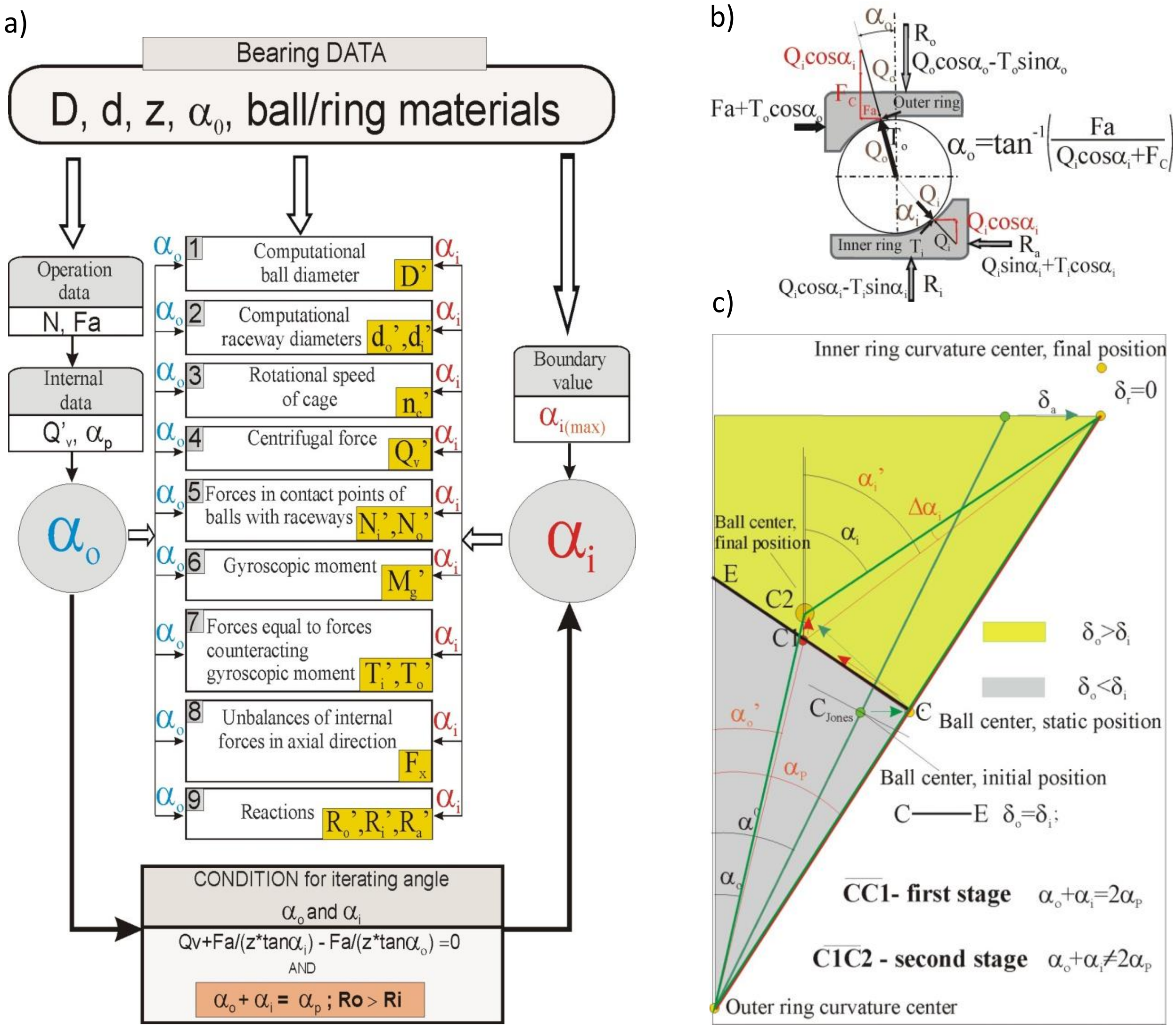


Fig. 10. Comprehensive mathematical model of loads in high-speed bearing: a) algorithm of first stage, b) equilibrium of forces, c) methodology of searching for equilibrium angles [15]

In addition, the spindle itself undergoes contraction between the supports by ΔA and the spindle nose by ΔB. In Fig. 11b the two models are jointly verified, by comparing the simulation results with the results of measuring the slid able sleeve motions occurring during changes in the rotational speed of the cold spindle.

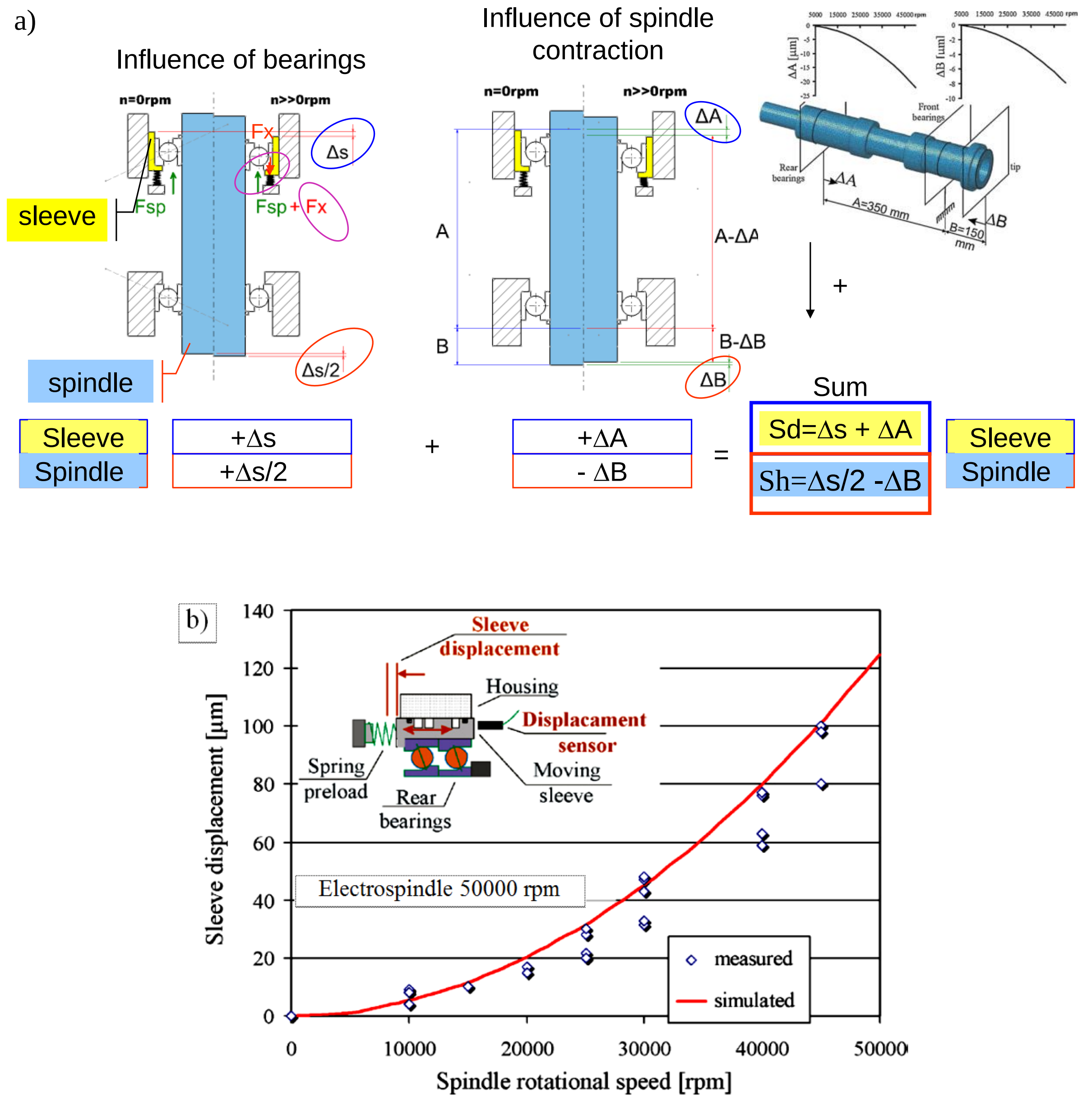


Fig. 11. Model of sleeve and spindle nose displacements (a), model verification for sleeve displacements (b) [12]

An example of the changes in the position of the high-speed spindle, determined using the models shown in Figs 10 and 11, is provided in Fig. 12. For the rotational speed of 50000rpm the spindle shift amounted to 40µm, the thermal displacement of the spindle relative to the base in a thermally stable state amounted to 68µm and that of the tilting table relative to the base amounted to 5µm. The determination of the thermal error through its prediction is subject to constant holistic improvement to ensure agreement between the obtained values and the ones which will actually occur during machine tool operation.

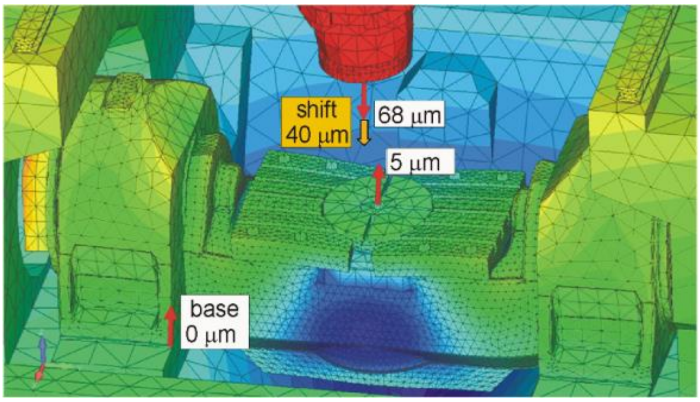


Fig. 12. Thermal deformations of 5-axis machining centre and spindle shift calculated for 50000rpm [15]

In the case of the feed axes it is essential to ensure the highest possible positioning accuracy. This requirement constantly grows, but feed rates, accelerations and jerk also keep increasing. In ball screw drives, which predominate in machine tools because of their much lower cost than that of direct drives, the error model is very complex [2]. The feed rates offered by ball screw drives have recently significantly increased to as much as 50-60m/min (80-100m/min in the case of linear drives), the accelerations amount to 0.7-1.2g and in special cases to as much as 2g (2.2-4.3g for linear drives). Inexpensive rotary encoders are used for ball screw drives while steel, quartz or magnetic linear encoders are used for linear drives. The latter encoders ensure much higher path measurement speeds than optical encoders and are often used in HSC machine tools, ensuring a resolution of 10nm and good path measuring precision at a feed rate of up to 50m/min. Intensive research is conducted to increase this speed.

The positioning errors of ball screw drives mainly depend on thermal deformations which change fast due to the high motion dynamics and the low thermal capacity of the ball screw and the nut. The two components are pre-loaded, but this load keeps changing during drive operation, together with the power losses in the nut and in the bearings, mainly because of the thermal elongation of the screw itself and the thermal and force displacement of the bearing supports. In order to precisely evaluate positioning errors one needs a holistic model incorporating a moving heat source. The temperatures and displacements versus the length of the pause in the duty cycle for the outermost position of the slide are shown in Fig. 13 [16]. The reciprocating movement took place along the distance of 400mm at a maximum speed of 30m/min until temperatures and displacements stabilized. The thermal displacement of the ball screw in the axial direction, which occurs at the end of the screw, corresponds to the maximum slide positioning error which may occur along the whole distance. For a pause of 2sec, after about an hour long operation, the displacement/positioning error amounted to 15µm. These are high values and should be compensated.

The holistic thermal machine tool model must take into account the influence of both internal heat sources and external heat sources characterized by low dynamics (e.g. variable ambient temperature) [19]. In practice many machine tool producers take into account only the error component due to ambient temperature variation.

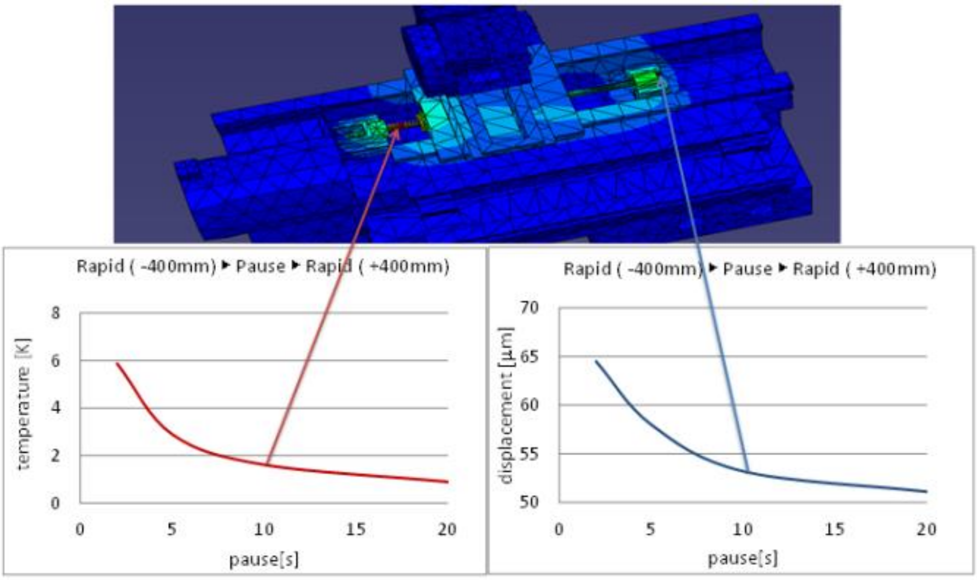


Fig. 13. FEM computations for lathe centre during drive work in Z axis with reciprocating movement < Pause ▸ Rapid movement (distance -400mm) ▸ Pause ▸ Rapid movement (distance +400mm) > at axis speed of 0.5m/s [16]

Some producers consistently pursuing the thermal error minimization strategy take into account both the components, using their own models. For example, the Yamazaki Mazak Corporation has developed an Intelligent Thermal Shield System (Fig. 14) [38].

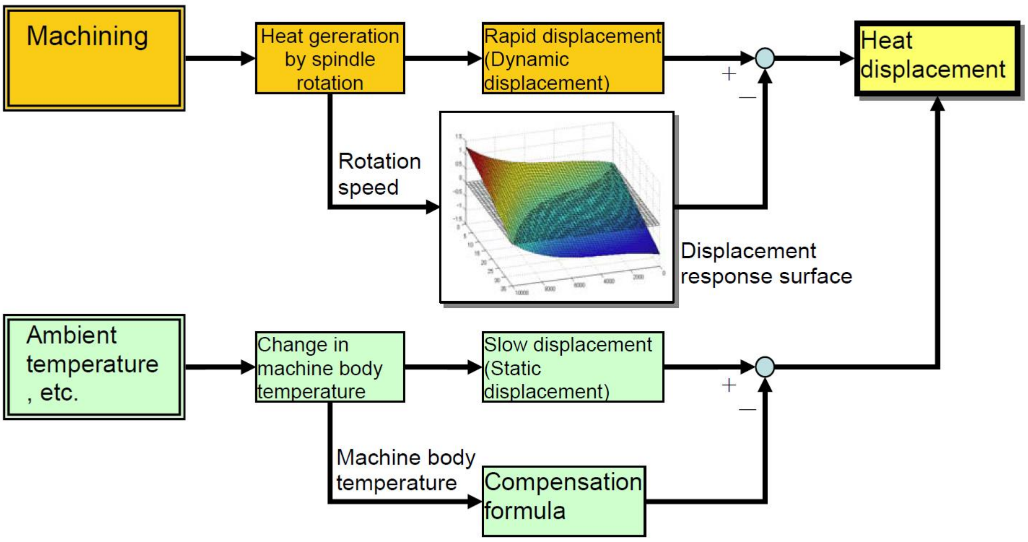


Fig. 14. Intelligent Thermal Shield System chart [38]

In this system the displacements caused by the variation in ambient temperature are determined as a product of the variable temperature rise and a special coefficient. The rapid displacements of the spindle are determined on the basis of a Displacement Response Surface which is a function of the displacements (in μm), the spindle rotational speed and the displacement speed (in μm/min) being a function of the rotational speed.

Thanks to the application of the Thermal Shield System to the reduction of the thermal error of a multitasking turning-milling centre at a spindle rotational speed of 12000rpm the error was reduced by over 80%. This is a good compensation result. A similar compensation result can be obtained using the multi regression function and taking into account the displacement speed parameter. Other simpler methods, including the ones based on fuzzy logic, reduce the error mostly to below 80% [40]. Better results can be obtained only in the case of very high machine tool symmetry and low error dynamics, or when compensation can be reduced to only one axis [8]. Most studies of compensation effectiveness are conducted at idle running [9]. In comparison with such results, compensation in natural machining conditions generally is at a level of 60%. Moreover, the above examples of compensation are mostly for spindle rotational speeds below 20000rpm at which error variation dynamics is usually low. At very high thermal stability of the machine tool one can sometimes achieve satisfactory compensation results, in most cases when the forced cooling in the area of large heat sources is well designed and works effectively.

In research still much emphasis is placed on the identification and reduction of the errors arising in the course of the machining process on their compensations [14],[24],[32]. Very good effects are brought about by integrating the machine tool with the control system through the use of highly efficient software tools facilitating superfast and precise machining. Instead of using strictly dedicated process models, 3D data are entered directly into NC. The segmental straight-line approximation of the path profile is today being replaced by continuous-line approximation ensuring good fit to the required profile. Profile control is adaptive and its essential element is the computation of the values of torque and its control in order to avoid chatter [35]. The instantaneous acceleration and deceleration values and interpolation are controlled whereby much greater accelerations of the feed motions than the initial ones are achieved. In this way high feed stability during profile shaping and so high accuracy of the profile being shaped and low roughness of the surface being machines are obtained.

The OKUMA Corporation, among others, has demonstrated how vital it is to include the largest possible number of error components. When the number of compensated error components in the function compensating the spindle head axis position error was increased from 4 to 11, the error decreased from 12μm to 4μm. An equally innovative design, control and software solution is used by the MORI SEIKI Corporation in both its own machine tools and the ones produced jointly with DMG. The location of drives in the centre of gravity of the shifted assemblies developed by Diedesheim initially and contrived somewhat by Toshiba Machine after then, which significantly increases dynamic stability, has become a norm. In order to minimize machining errors MORI SEIKI has adopted a solution, developed initially by Toshiba and applied to the vertical machining centre, in which the milling-turning centre tool head is located on an octagonal frame equipped with four mutually skew guides owing to which the centre of the shifted frame occupies a constant position. This ensures high feed precision and rates, the self-compensation of thermal errors and good vibration damping. In order to reduce thermal positioning errors in the feed axes for ball screws the latter are longitudinally cooled through their centre and around the nut. Errors resulting from the thermal elongations of the spindle are reduced in a similar way. Tool control commands apply to the tool tip point, i.e. the cutting point, whereby there is no need to track the tool length. The cooling of the cutting fluid (which increases energy consumption) is used to increase machining precision. The energy saving functions implemented in the machine tool reduce its heating up, but complicate its modelling.

The accurate milling of complicated profiles requires the reduction of errors caused by the variable deformations of the milling cutter. Research is underway to minimize its length. Therefore systems for optimal length determination are created and improved (Fig. 15).

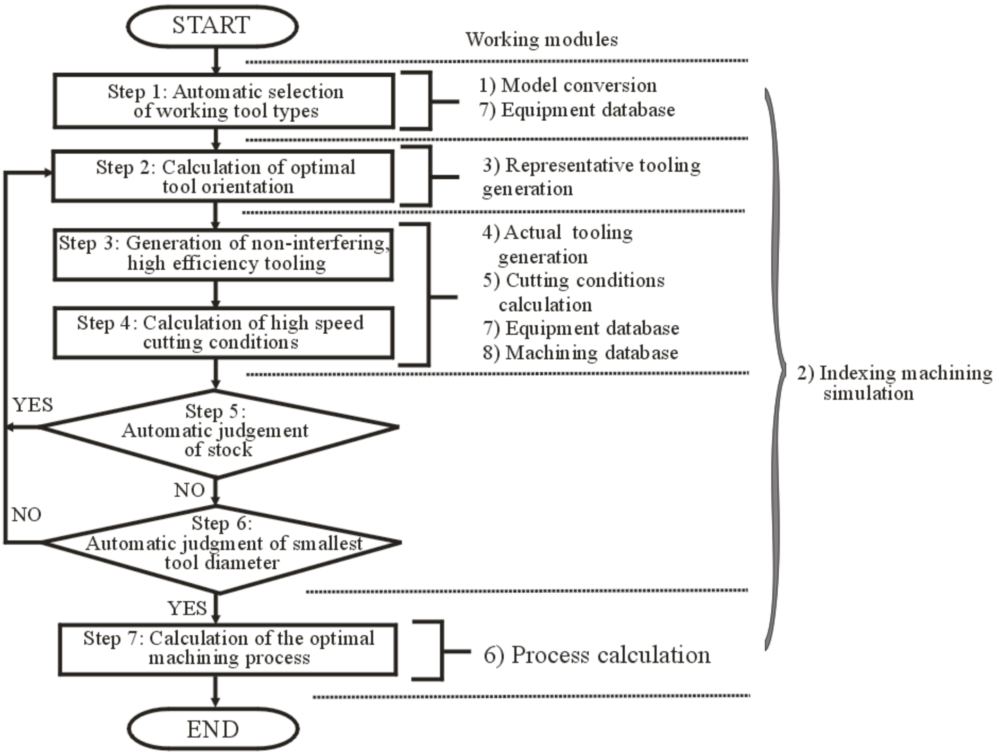


Fig. 15. System processing flow & positioning of individual modules [44]

The spindle torque in the five-axis MAKINO machining centre reaches 1500Nm, ensuring titanium machining output of 500cm^3/h. The centre's guides are rectangular, very stiff and ensure good vibration damping. The spindles of the centres have been so designed that they meet the requirements for machining different materials. They are also equipped with procedures for preventing self-induced vibrations. The housings of the centres are cooled from the inside through the flow of fluid with controlled temperature, whereby the temperature is vertically and horizontally uniformed. This prevents deformations caused by changes in ambient temperature. In addition, the linear motors are actively cooled while the bed and the columns are thermally insulated from the influence of the cutting process.

There is a trend towards modelling the machine tool and the process jointly and towards virtualization, aimed at flexible control and disturbance minimization through the active control of disturbances and error values. But active control requires very expensive mechatronic modules [29] and highly efficient control systems. The virtualization of the machining process aimed at increasing machining precision is still limited due to inaccurate modelling [3],[24]. The precise modelling of heat transfer [4],[20] and its active control [16] are essential.

The holistic improvement of spindle units based on the latest research [1],[42], especially aimed at improving the dynamic and thermal stability, implementing adaptronics and actively reducing errors arising in real time, is vital for increasing machining precision. Soshi [36] has shown that by equipping the spindle unit with a synchronous motor (instead of the induction motor) and a proper controller almost invariable rotational speed is achieved, whereby machining process stability greatly increases. Brecher has demonstrated [6] that the holistic modelling of the couplings between the double spin machine and the milling process leads to the greater stability of parallel milling and significantly facilitates the optimization of the process. He also obtained very good agreement between the results of depth-of-cut stability simulations and measurements.

It is anticipated that the use of new construction materials (ceramics, composites and porous materials) for spindle and feed assemblies and load-bearing frames will substantially contribute to greater thermal and dynamic stability. Composites are 2.5 times lighter and their damping coefficient is 22 times higher and although their cost is a barrier to their use, they enable a great increase in the dynamics of HSC processes and in resistance to thermal disturbances. The application of such materials will open up possibilities for creating innovative machine tools for the aviation and medical industries.

5. CONCLUSION

The market-driven development of machine tools aims at achieving increasingly higher machining process efficiency. It is based on a general manufacturing development strategy and should be consistent with the trends in the development of products and factory business. In order to ensure high synergy of user benefits the development of machine tools must be holistic, based on the holistic modelling and numerical simulation of machine tool operational properties and maximally exploiting innovations and the latest knowledge. New machine tools should be increasingly digitalized and equipped with intelligent functions, which will result in a large increase in efficiency and so in manufacturing precision and cost reduction. Energy saving must be a major premise in the creation of new machine tools, which will lead to their higher precision and longer lifetime.

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