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# METHODS OF MACHINE TOOL ERROR COMPENSATION

The most important tendencies in the development of modern machine tools are pointed out, including the improvement of their design and development of error compensation methods. An overview of the most popular and useful error compensation methods for machine tools is presented. Based on examples, the effectiveness and limitations of each method are discussed. An integrated 5-axis machine tool behaviour model is presented, which assists in the elaboration of an error model required for the compensation purposes.

## 1. INTRODUCTION

Together with the increase in requirements concerning the precision of manufactured goods, machine tools and manufacturing systems are faced with constantly higher requirements. Emphasis is especially put on the increase in performance with simultaneous improvement of machining precision [18]. In order to achieve and sustain precision in range of few micrometers it is required to monitor and compensate a series of various types of errors. These are especially geometrical, kinematic and thermal errors, as well as these caused by cutting forces, etc. Such errors can be significantly reduced, but usually cannot be fully eliminated [21]. The increase in accuracy of machine tools is achieved by improving their structure, introducing innovative design solutions for particular assemblies, increasing precision of manufacturing components of machine tools and their assembly, as well as by applying error compensation methods.

Design solutions increasing precision can include e.g. application of materials with low thermal expansiveness and high stiffness, assurance of design with thermal symmetry, application of effective cooling and correction systems, etc. However, even best design solutions usually do not allow achieving required precision. Such is caused mainly by constantly appearing external and internal disturbances which limit the possibility of achieving high machining accuracy. Due to this fact, various compensation methods are applied, oriented on particular types of errors. The selection of these methods depends on

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the behaviour of errors in time and on their level of complexity. Error compensation can be realised by introducing corrections to machine tool controllable axes or by motion trajectory correction relatively to machined workpiece, which is introduced to tool path.

Machine tool accuracy can be increased both during their design process and during its exploitation. In these two improvement areas it is possible to apply various type of activities (Table 1).

Table 1. Areas to improve the accuracy of machine tools

| Design area | Exploitation area |
|---|---|
| • Increase of component precision<br>• Proper machine tool assembly<br>• Minimisation of heat sources<br>• Limitation of heat phenomena influence<br>• Active error correction | • Avoidance of rotational speed changes in a broad range<br>• Reduction of ambient temperature changes and thermal interactions from the cutting process<br>• **Application of error compensation methods** |

According to Table 1 there are many ways to increase machine tool accuracy. All of such methods can be classified to one of two shown groups. First of them incorporates solutions which aim at the minimisation of errors. Main problem in this case is error minimisation cost which increases exponentially with the increase of machine tool accuracy. For machines built for precise machining, the selection of a minimisation method is of high importance since excessive cost can raise doubts about the cost-effectiveness of applying a too expensive machine tool. Therefore, more and more often the accuracy of machining is increased by means of methods from the second group, especially error compensation methods [5],[38].

The implementation of an error compensation method is carried out in the following three phases [16]:

a) **Identification:**
analysis of machine tool structure, definition of appearing error types, identification of optimum positions for measurement sensors, measurements of particular component errors in various operating conditions, determination of volumetric errors or a map of geometric volumetric errors.

b) **Error modelling and forecasting:**
elaboration of component error models, inclusion of single error models into a complex machine tool error model, elaboration of error maps, numerical forecasting of error values in operational conditions.

c) **Compensation:**
installation of an error compensation system, implementation of compensation algorithms or error maps to the control system.

## 2. ERROR COMPENSATION IN MACHINE TOOLS

Each machine tool has a defined accuracy with which it is able to manufacture elements, since it is very difficult to eliminate all its errors, both after-assembly and these taking place in the operational conditions [29]. Due to this fact machine tool designers utilise various techniques of increasing the accuracy of machine tools themselves and the machining process. In many cases it turns out that the construction of a very precise machine tool is extremely difficult, labour consuming and, most importantly, very costly [29]. It is much easier to apply error compensation. Effective compensation allows manufacturing pieces with high accuracy, even with the use of a medium-precise machine tool [35]. When a machine tool is not able to manufacture elements with required precision, it is possible to apply a different machine tool which however is often impossible for many reasons, such as inability to access one, extension of production time, excessively large changes to a production line, etc.

But to ensure the effectiveness of compensation, the identification of errors must be very precise, compensation algorithm must be properly elaborated and adapted to the control system, as well as a map of geometrical and post-assembly errors must be properly defined. It must be taken into consideration that not in all cases compensation yields expected results – it can improve machining accuracy only slightly. Whereas its implementation on a machine tool is usually connected with the realisation of time-consuming investigations, tests and measurements. Such always generates additional costs [28].

As is shown by research [6], in case of a precise and very precise machine tool compensation is usually indispensable and best tool for improving the quality of machined pieces. Based on the experience of machine tool manufacturers, manufacturing and subsequently exploitation costs of super-precise machine tools are very large and it is very difficult to find clients for them. One must remember that the goal of compensation is only "improvement" of precision of the existing structure, which always depends on the level of initial post-assembly accuracy of the machine which should be as high as possible, and what is especially important, such accuracy should be repeatable. It should also be taken into consideration that compensation should regard all important errors influencing machining accuracy [17]. Problem is in ensuring that such errors are both repeatable and as low as possible, which greatly facilitates ensuring effective compensation.

When it comes to achieving a precise, thermally stable machine tool [20], i.e. a machine which deforms in a small degree as a result of temperature changes and which behaviour in operational conditions is repeatable, then fulfilling its characteristics mentioned before is a good base for introducing error compensation. Together with the advance in technology, microprocessor units for following and monitoring errors, precise measurement sensors and new tools for mathematical analysis have become easier accessible and less expensive. Thanks to such means, the introduction of active error compensation has become easier.

Presently in many research centres and machine tool factory all over the world, very intensive research is conducted on the development of error compensation methods.

A series of sophisticated error models has been elaborated based on the application of various types of tools and their mathematical modelling. The most important include:

- linear and non-linear regression,
- neural networks,
- fuzzy-logic,
- transfer function,
- grey system theory,
- B-splines and NURBS surfaces,
- independent component analysis,
- HTM (Homogenous Transformation Matrix).

In the industrial applications, linear and non-linear regression is of most importance due to model simplicity and ease of implementation. Investigations are conducted in research centres aiming at the utilisation of neural networks and fuzzy logics for error compensation purposes. Based on the above mentioned mathematical modelling tools various error compensation methods have been elaborated, the most useful of which are presented in further parts of this paper.

Each compensation method has its individual characteristics. These can include [30]: versatility, uncertainty/accuracy, compensation realisation time, method of acquiring data from a machine tool. Based on above listed characteristics it is possible to assess if a given compensation method can be used with a particular machine tool, whether its application will bring satisfactory reduction of machining errors, but most importantly, if time needed for its realisation is not too long.

## 3. TYPES OF ERROR COMPENSATION METHODS

The essence of machine tool error compensation lies in their measurement or forecasting in real time and based on it introducing proper corrections to the control system or to tool path. Based on the method of determining errors, the following methods of error compensation are distinguished:

- **direct sensor-based methods** based on a direct error measurement by means of sensors distributed in working space of a machine tool,
- **indirect sensor-based methods** based on error forecasting with the use of their mathematical models which utilise information e.g. from temperature measurements in characteristic locations of machine tool structure, from measurements of geometrical errors and from measurements of deformations,
- **indirect sensorless methods** based on error forecasting using a mathematical model which utilises machine internal data, e.g. spindle rotational speed; in these methods dedicated sensors placed on a machine tool are basically not used – only these which are integral part of drive control systems for controllable axes.
- **hybrid methods** based on error forecasting based on mathematical models which use information e.g. from temperature and deformation measurements in characteristic points of machine tool structure and also take into consideration internal data

of a machine tool, such as spindle rotational speed, feed, as well as ambient, motor, ball screw nut temperatures, etc.

- **other methods** highly dedicated.

## 3.1. DIRECT SENSOR-BASED ERROR COMPENSATION METHODS

In direct error compensation methods machine tool error is measured periodically. Important advantage of these methods is direct error measurement which is to be corrected by the compensation. As measurement systems, laser devices or measurement probes are most often applied. With regard to the change of error characteristics with machine tool operation and machining process parameter changes, as well as environment influence, such values require updating. Compensated errors can be followed in a constant or periodical manner and can be monitored. The need of realising frequent measurement causes interruptions to the cutting process and in consequence reducing machining effectiveness. The higher frequency of conducting measurements, the lower effectiveness of applying this method. Additionally, precise error measurement in working space of a machine tool, dependent on the applied method, causes many problems connected to numerous disturbances coming from e.g. cooling agent, chips, rotating spindle, covers, etc. With regard to limited amount of room in working space there can also be problems with installing a proper measurement system. The popularity of direct compensation methods, despite significant advantages, is therefore greatly limited. They are applied mainly in grinders in which constant error measurement is preferred.

## 3.2. INDIRECT SENSOR-BASED ERROR COMPENSATION METHODS

### 3.2.1. METHODS OF THERMAL ERROR COMPENSATION BASED ON LINEAR AND NON-LINEAR REGRESSION

For error compensation, usually indirect methods are applied in which quantities are measured which are easier to acquire, e.g. in case of thermal errors - temperature in specific machine tool points [9-11], [23-25]. Errors to be compensated are forecasted based on a mathematical model of the entire machine tool or one of its assemblies which has a decisive role in generating such error. By applying indirect compensation methods errors can be followed and monitored in real time, independently from the cutting process, without the need of interrupting it. The basis of such monitoring in case of thermal errors is constant observation of temperatures. However, a disadvantage of indirect error compensation methods is the need of fitting a machine tool in costly sensors and measurement systems.

Indirect sensor-based compensation methods, in order to determine a mathematical model of errors in form of a polynomial, usually utilise linear or non-linear regression. Based on it corrections of machine tool errors are introduced. Such function is mainly applied for compensating thermal errors. Input data of these functions are temperature values acquired from sensors placed on a machine tool, while their output is in form of needed correction values for controllable axes.

The main problem here is to localise these heat sources which in greatest degree influence the change of machine tool accuracy, i.e. thermal displacements accompanying temperature changes. This is usually accomplished based on technical documentation of a machine tool and on a numerical analysis of identification measurement results for temperatures and thermal displacements. Such numerical analysis verified experimentally allows very precise identification of the error model for a broad range of operational parameter changes, machining conditions and environment influence. In places where, according to the analysis, temperature rise significantly influences thermal errors, temperature sensors are installed. Fig. 1 shows a structure of a high-speed machining centre with sensors for temperature measurement of particular machine components, arranged based on the conducted numerical analysis.

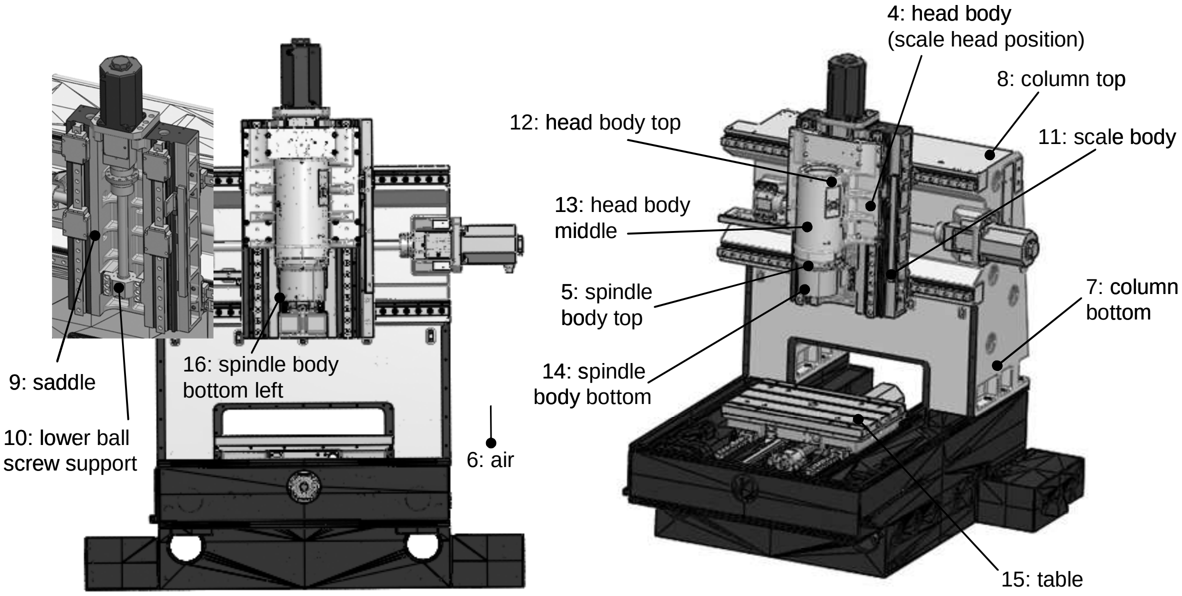

Fig. 1. Location of temperature sensors [22]

During the exploitation of machine tool and the realisation of compensation, measurement sensors constantly provide information about temperature levels in selected machine tool spots. Amount and location of the sensors must be optimally selected [12], [38], i.e. their minimum amount is only taken into consideration and their location in places which decide about displacements. In this selection, only these sensors should be included which are in points where temperature change has an important influence on the machine tool accuracy. In case of taking too many sensors into considerations, the form of correction function becomes excessively complicated and can degrade its precision. Too small amount of sensors does not ensure precise enough error forecasting. As it was mentioned before, the best method for selecting amount and locations of temperature measurements is based on utilising a model and simulating thermal behaviour of the machine tool. After conducting the accuracy analysis of the polynomial correction function its final form is defined which should be as simple as possible [22], in order to enable its simple implementation in the machine tool control system and allows compensating in the on-line mode.

Fig. 2 presents the relationship of the accuracy of the correction function with its complexity level (amount of temperature measurement points) and with the localisation of sensors for the operation of machine tool in idle mode. Numbers of temperature measurement points correspond to these shown in Fig. 1. In case of some correction functions, spindle rotational speed (Rss) was additionally taken into consideration. Fig. 2 shows that the best accuracy (max. error = 10,7 μm) was achieved for the correction function which arguments are 6 temperature measurement points (8, 9, 12, 13, 14, ambient temperature) and spindle rotational speed. However, the best solution for this machine tool is the corrective function with max. error of 11,0 μm which arguments are 3 temperature measurement points (12, 14, ambient temperature) and spindle rotational speed. This function predicts error values almost equally as good as the previous one, but utilises two times less sensors which simplifies the form of this function and lowers the cost of the compensation system.

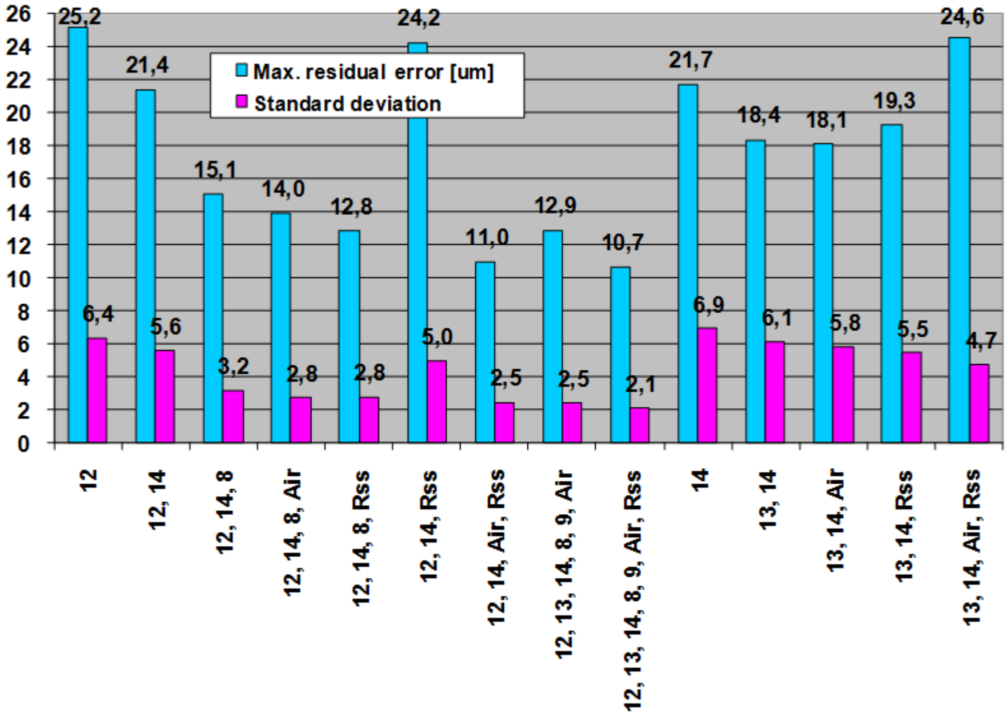

Fig. 2. Thermal errors for use of different input data sets to compensation function
- number and position of temperature sensors, spindle rotational speed and air temperature [22]

Sample results of compensation with the use of elaborated polynomial correction function for spindle rotational speeds varying in time are shown in Fig. 3. During investigations, rotational speed was altered every 30 min. according to the following sequence: 12000, 16000, 8000, 14000, 6000, 10000, 18000, 20000, 8000, 0, 4000, 1000 rpm. The correction function was entered to the control system of a high-speed machining centre. Fig. 3 presents the comparison of measured axial thermal displacements of a spindle tip after enabling compensation (curve 1), predicted thermal displacements of a spindle tip with the use of thermal error model (curve 2) and thermal displacements of a spindle tip which would appear without compensation (curve 3). By comparing curves 1 and 3 it can be noted that thermal displacements of a spindle tip in the Z direction, as a result of applying compensation, were reduced from ca. 95 μm to ca. 18 μm. The application of compensation therefore increased machine tool accuracy few times.

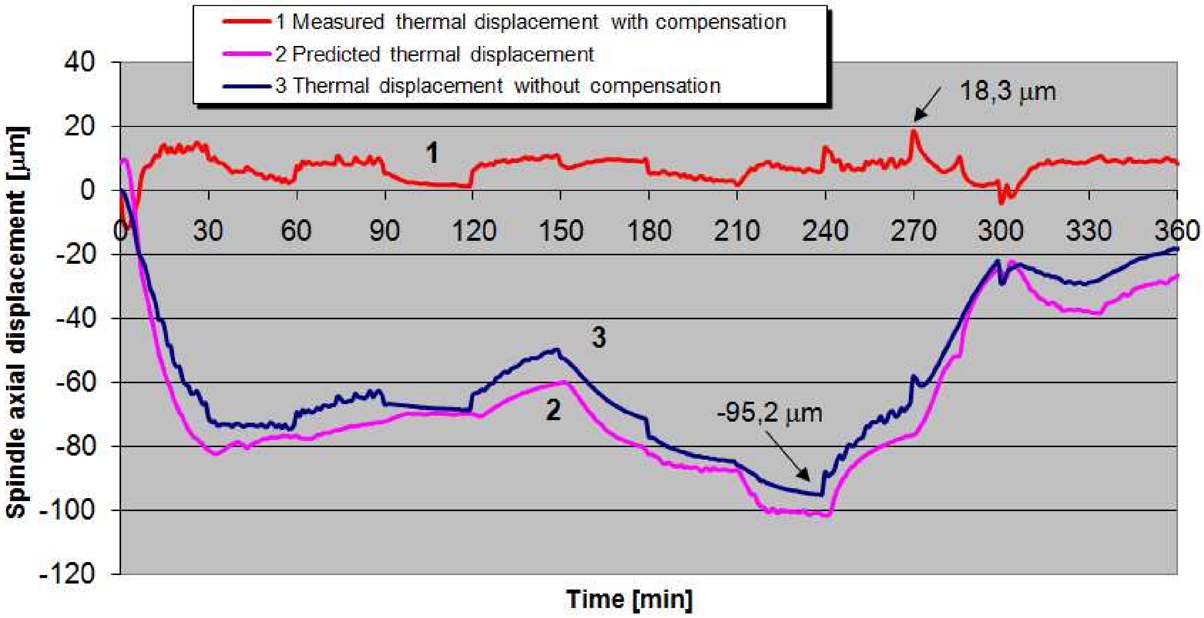

Fig. 3. Efficiency of high-speed machining centre spindle thermal displacements compensation in Z direction [25]

### 3.2.2. COMPENSATION METHODS BASED ON NEURAL NETWORKS

In the field of machine tool development, neural networks are used mainly for minimisation of thermal errors [26]. Based on data acquired from the machine and measurement system which define real position of spindle and temperature of machine tool components (Fig. 4) it is possible to define the difference between actual and desired state, i.e. predicted thermal error of a machine tool in the analysed controllable axis. Data acquisition process can be realised at constant, rising or randomly varying spindle rotational speed [26]. Based on acquired data, a neural network must be trained with the values of needed spindle tip location correction by the control system at specific operational parameters, such as spindle position, ambient temperature, spindle rotational speed, etc. Data acquisition process can last for a few to few tens of hours. After this time has passed, it can be assumed that the neural network can generalise the problem, which means that it can provide proper error correction values for operating parameters varying in predefined ranges.

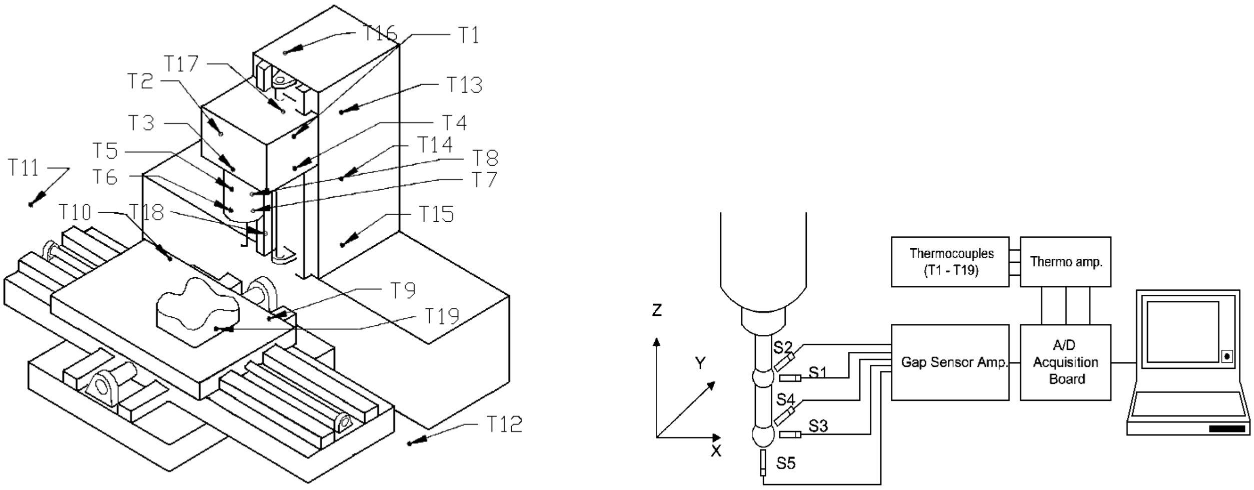

Fig. 4. Location of thermal sensor and arrangement for measuring of spindle displacements [26]

Based on experimental investigations [4],[26] it can be assumed that the application of a neural network for compensating errors can increase machine tool accuracy even by 75-80%. However, with it arises a problem of unknown (implicit) form of a function, based on which compensation is realised. Even if one succeeds at defining such function in the explicit form, it will be much more complicated than e.g. polynomial function acquired by means of the regression analysis. This renders it difficult to implement compensation in machine control system and requires the application of an additional external computer. Another solution for such problem is the application of digital signal processors (DSP’s) which, compared to standard processors, are able to execute parallel mathematical operations. It must however be taken into account that the less complicated is the function, the quicker are calculations realised.

### 3.2.3. COMPENSATION METHODS BASED ON FUZZY LOGICS

Fuzzy logics can be applied in all places where it is impossible to use a mathematical model or when mathematical model could be excessively complex [27],[36]. Fuzzy Logic Controller (FLC) is composed of three blocks:

- fuzzification block which transforms numeric values to linguistic,
- inference block with a set of rules,
- defuzzification block defining output values.

An example of a practical application of fuzzy logics for compensating thermal errors is a method of modelling of such errors tested for a horizontal milling centre, described in paper [13]. Similarly as in case of the regression method or neural network method, temperature sensors were placed on the machine. Non-contact sensors were applied for measuring spindle thermal displacements. Depending on spindle rotational speed and feed value, three operation ranges of the machine were defined: standstill, slow operation, fast operation.

Table 2. Example of machine tool operating ranges in fuzzy logic method [13]

| | Rotational speed [rpm] | Feed [mm/min] |
|---|---|---|
| **Standstill** | 0 | 0 |
| **Slow operation** | 600 | 508 |
| **Fast operation** | 3000 | 2006 |

Particular operation cycles of the machine tool were started in a random order. During each cycle, data was gathered concerning temperatures of single components of the machine and about thermal displacements of the horizontal milling centre. On such basis it was possible to assess the relationship between displacement and temperature. Initially a large amount of temperature sensors was installed on the machine tool – in this case 14. For such number, however, a problem arose with the optimisation of the model. For this sake, so called backwards elimination was applied, i.e. data from the sensors which had no significant influence on the spindle tip location was rejected.

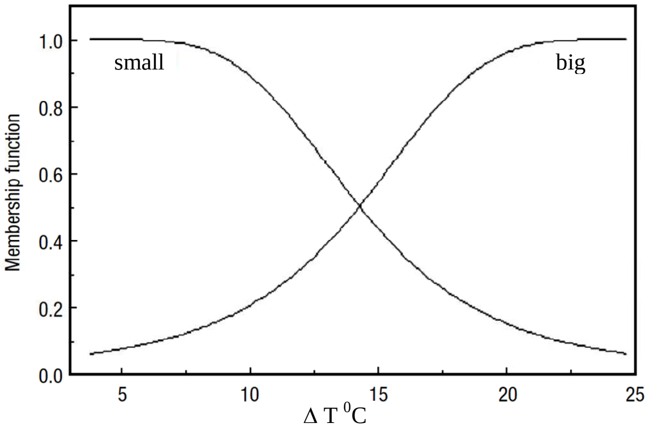

Fig. 5. Membership function for the variable ΔT [13]

After conducting optimisation three sensors were selected, for which two linguistic variables were defined – small, big (Fig. 5).
Next, fuzzy values were used to create conditional instructions which general form can be written as:

If ΔT is small, then thermal displacement = ...
If ΔT is big, then thermal displacement = ...

where ΔT is the increment of temperature in a measurement point which has the most significant influence on spindle tip position changes.

Fig. 6 presents the comparison of measured error values with error obtained with the use of fuzzy logic model (3 temperature sensors), linear regression model (4 temperature sensors) and non-linear regression model (3 temperature sensors). Based on Fig. 6 it can be assumed that fuzzy logics correctly predicts error values while using a smaller amount of sensors than the amount used in the model based on linear regression and being less complicated in comparison to the model based on non-linear regression. Thermal error compensation with a smaller number of temperature sensors or with a simpler function form is more beneficial, in comparison to other methods, due to the limitation of sensor uncertainty influence and at the same time allows limiting costs.

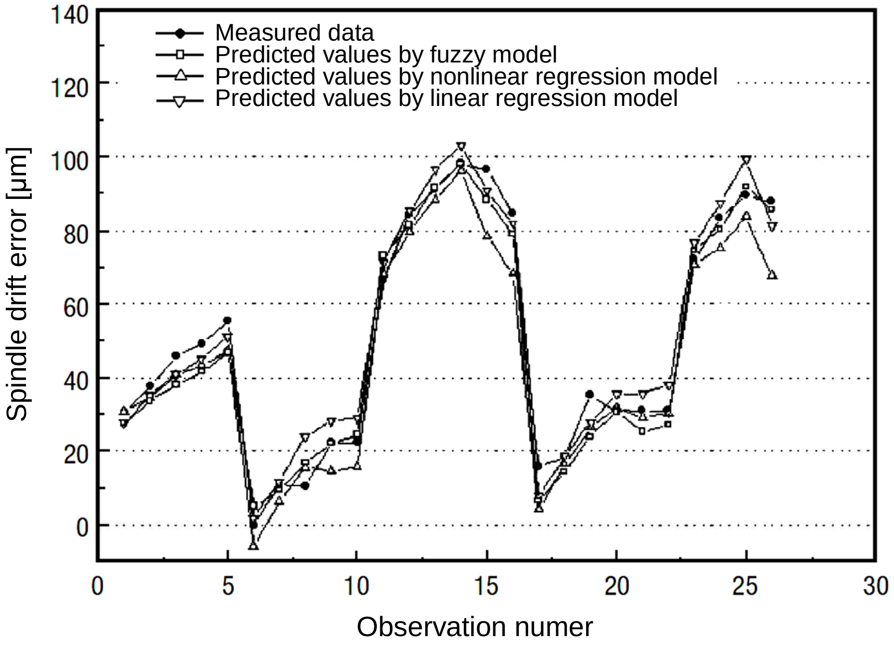

Fig. 6. Comparison of the measured error values with the use of values predicted by different methods [13]

### 3.2.4. COMPENSATION METHODS SUPPORTED BY A GREY SYSTEM THEORY

Grey system theory (GST) has been elaborated by J.L. Deng in 1982. This method can be used to search for relationships between various quantities, for modelling and forecasting short-period time series in which data is incomplete and uncertain, as well as to help in decision making [3].

In machine tool error compensation, grey system theory is used to support other mathematical modelling tools, such as neural networks, linear regression and fuzzy logics [33],[34]. An example of utilising the GST method is the minimisation of temperature sensors to be used for defining the correction function. Based on measurement results of temperature increments in 7 points of a machining centre (12000 rpm) and thermal displacements in X, Y and Z axes (Fig. 7), with the help of the GST model, a ranking of sensors was built from the point of view of their usability for elaborating a precise correction function (Fig. 8). In the analysed case, three sensors were selected: T2, T6 and T7, because temperatures measured by them had the most significant influence on thermal

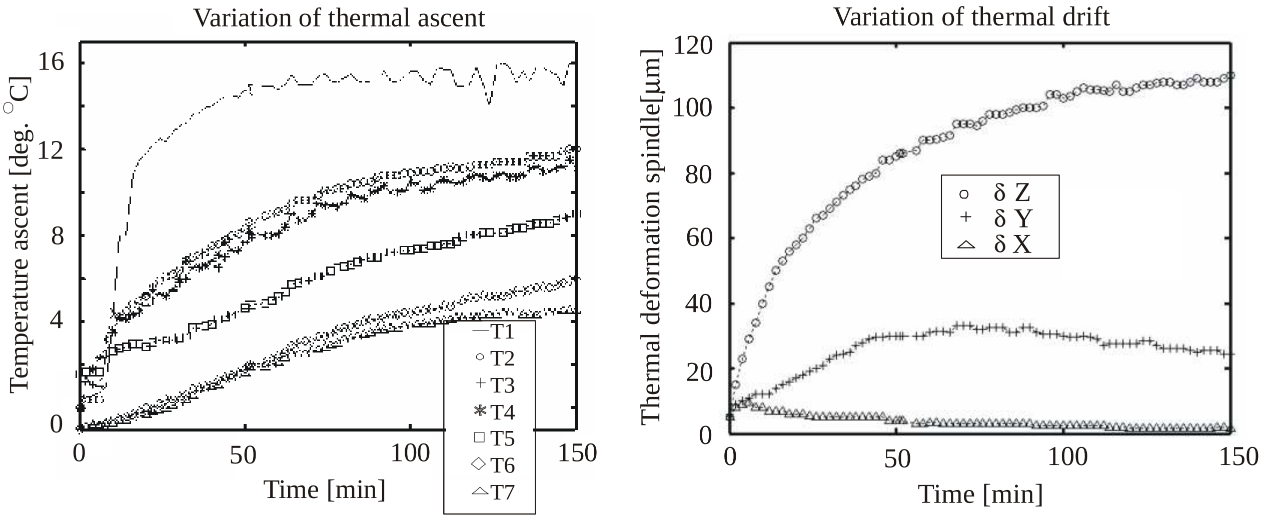

Fig 7. Temperature ascent with time and variation of thermal deformation of spindle nose in the X, Y, and Z directions [34]

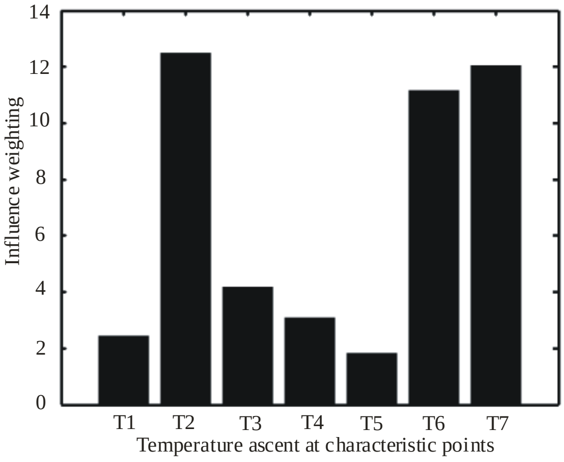

Fig. 8. Influence ranking of temperature ascent on thermal deformation of spindle nose in Z direction [34]

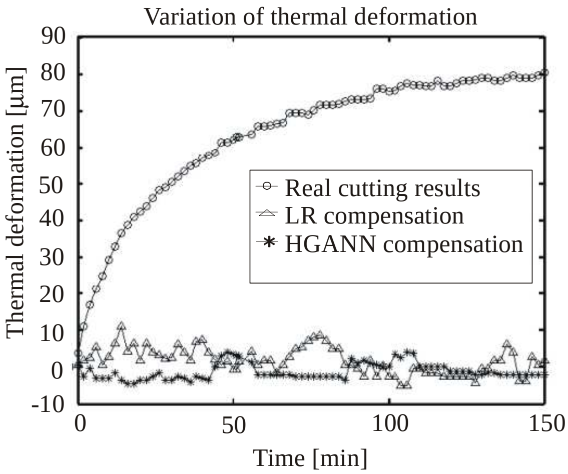

Fig. 9. Comparison of the thermal error before and after compensation [34]
where: LR compensation: compensation with the use of linear regression
HGANN compensation: compensation with the use of neural networks supported by GST

displacements. Resignation from the remaining 4 temperature sensors, since they were insignificant, allowed accelerating the construction of a machine tool error model and simplifying it while retaining its high accuracy. Fig. 9 presents the comparison of thermal displacement without compensation and with compensation with the use of two methods: linear regression and neural networks supported by GST. The results point out that compensation supported by GST is better than compensation based on linear regression.

### 3.3. SENSORLESS ERROR COMPENSATION METHODS

A series of scientific investigations was conducted [19],[31] which aimed at the verification of possibilities for applying a so called sensorless method in machine tools. Such sensorless method is based on thermal error compensation of a machine tool based only on its internal data. It does not use temperature sensors specially distributed to various places on a machine tool, as it is with sensor-based methods. Compensation is realised based on a previously defined thermal characteristic of a machine tool, which depends on spindle rotational speed and signals from sensors which are by default placed in e.g. drives. However, this method can only be applied in case when temperature and displacement runs are consistent with these of first order inertial element and when they are repeatable. Results from experimental investigations show that such runs are hard to achieve and additionally, machine tools usually do not have fully repeatable and predictable thermal characteristic. In order to achieve full repeatability of machine tool thermal behaviour it would be necessary to apply special procedures of individual perfection of each machine tool. Known examples of the application of such method apply to machine tools with relatively low spindle rotational speeds.

### 3.4. HYBRID ERROR COMPENSATION METHODS

Sensor-based and sensorless methods utilise completely different parameters to generate a correction function. In high-speed machine tools none of these ensures the obtainment of fully satisfying results. Therefore a so called hybrid compensation has been elaborated [21], which connects sensor-based and sensorless methods, utilising both sensors for temperature measurements and machine’s internal data, especially spindle rotational speed. Based on research [2],[8],[21] it was wound that in high-speed machine tools, apart from errors caused by thermal deformations, there is a problem of sudden spindle shifts in the axial direction during rotational speed changes. Errors resulting from spindle shifts, which reach couple of tens of μm, superimpose on thermal errors.

Hybrid compensation method uses temperature measurement sensors for compensating thermal displacements, while machine’s internal data in form of spindle rotational speed are used to compensate spindle shifts. The magnitude of such shifts can be acquired from experimental data on a machine tool or can be defined by an elaborated mathematical model [8]. In Fig. 10 a comparison of measured spindle displacements without compensation (dark blue line) with displacement after compensation (red line) is shown for machine tool duty cycle shown in the upper part of the Fig. 10. Displacements forecasted based on the correction function of a hybrid error model are shown in Fig. 10 by means of a yellow line. Remaining error after introducing compensation, marked by a red line, is highest in the moments of spindle rotational speed changes from much lower to much higher speed. Despite sudden (few seconds) and large (couple tens of µm) spindle shifts, not connected with thermal state of the machine, a very significant decrease in error was achieved, which amounted maximally ca. 20% of its preliminary value.

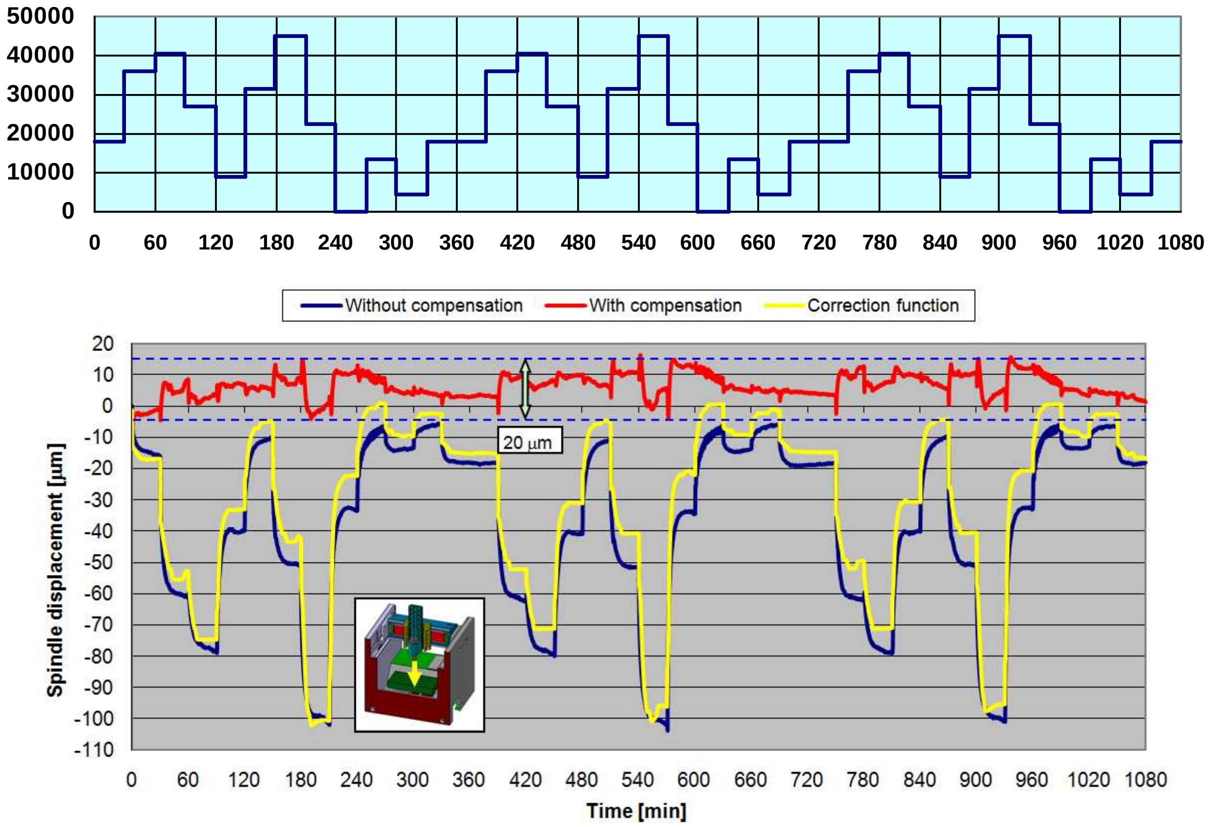

Fig. 10. Experimentally identified and predicted high speed machining centre spindle displacements and theoretical compensation results [21]

### 3.5. OTHER MEHTODS OF ERROR COMPENSATION

#### 3.5.1. VCS SYSTEM

In 2008 during the International Manufacturing Technology Show in Chicago, Siemens Energy & Automation Company proposed the supplementing their formerly elaborated error minimisation methods by a Volumetric Compensation System (VCS). In the proposed solution, the VCS software cooperates with the SINUMERIK 840D sl controller and is used to compensate geometric errors of a machine tool which can cause wrong position of a Tool Center Point.

VCS uses standard 21-parameter geometric error model. Thanks to this both linear and angular errors are taken into consideration [1]. Types of such errors are shown in Fig. 11. Main advantage of this method is tight integration of error matrices in machine tools with the SINUMERIK 840D sl controller. Such connection provides the possibility of running compensation algorithms in real time.

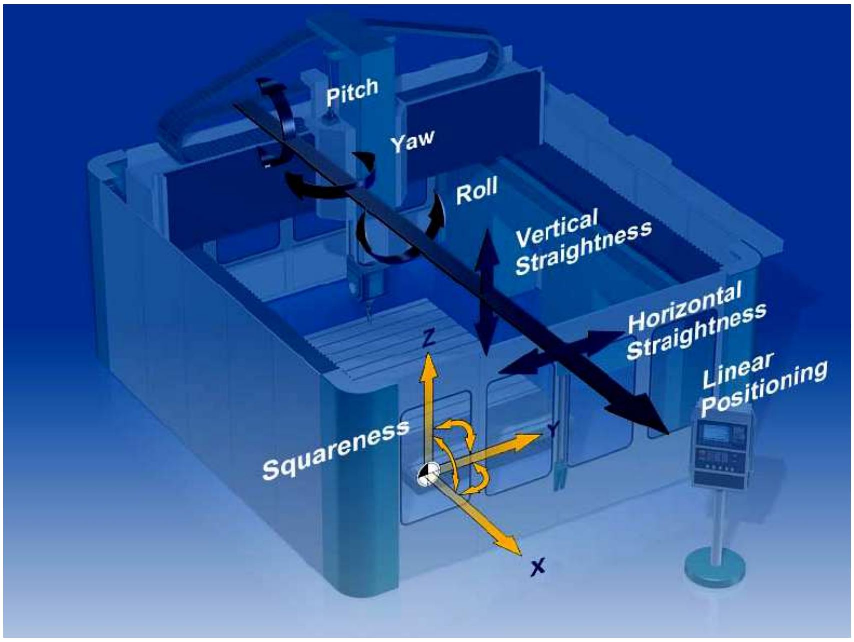

Fig. 11. Types of errors taken into account by VCS [2]

In order to apply the VCS method it is necessary to conduct measurements in the entire working space of a machine and to define values of all 21 error components. Such measurements can be performed with the use of a laser interferometer. The application of this kind of device gives the possibility of quick converting acquired results to a standard conforming with the SINUMERIK 840D sl controller [2]. After finishing of such process and reaching operation readiness state by the machine, control algorithms of the system begin their work. Such algorithms operate inside the controller’s interpolation cycle in order to match programmed and real position and tool tip point orientation.

The application of the described method causes accuracy increase averagely by 75-80% [1], but in some cases this accuracy rise is even higher. For example, during one of tests on a portal milling machine, the VCS system caused the minimisation of volumetric error in the full range of working space from 0,40 mm to less than 0,025 mm. It should be mentioned that the VCS system should be applied as an additional method of error reduction on machines already equipped in other widely available compensation methods, such as positioning error correction and reduction of backlash in the controllable axes.

Fig. 12 shows the reduction of roundness error thanks to the application of the VCS system, which allows achieving much more accurate arc trajectory.

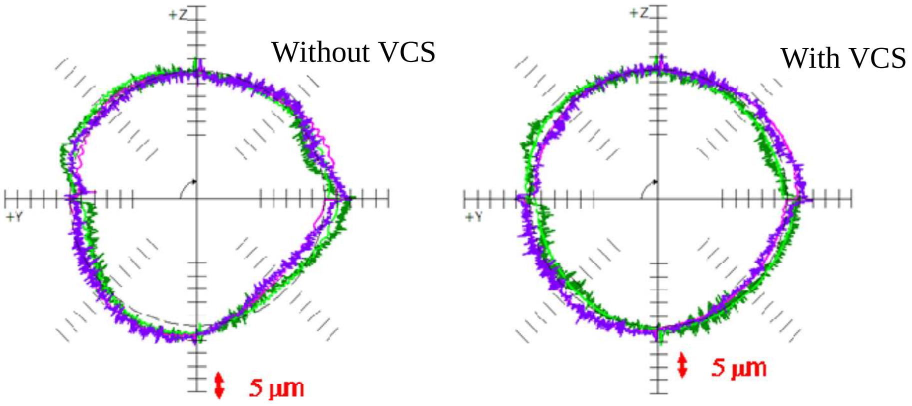

Fig. 12. Roundness error in the Y-Z plane - with and without VCS [2]

### 3.5.2. DECOUPLING METHOD

Currently in the industry, more and more popular are 5-axis machine tools. Thanks to two additional rotational axes they ensure proper tool paths at machining virtually any surface shape. Similarly as in case of 3-axis machine tools, also 5-axis machines generate different kinds of errors which require compensation. With regard to a larger amount of axes, the reduction of errors in 5-axis machine tools requires complex compensation methods.

In case of a decoupling method, accuracy measurements are conducted with the use of a 3D measurement probe. Detailed description of its use is contained in paper [15]. Based on measurements, a machine tool error model was elaborated [14]. In order to simplify the model, backlash compensation on all axes has been previously achieved and thermal errors were not taken into consideration.

In the decoupling method, compensation values are calculated separately for linear axes and for rotational axes. Firstly, compensation values for rotational axes are computed, then for linear axes. Fig. 13 shows ideal and real locations and orientations of a machine tool tip. Thanks to such solution, compensation of tool tip position includes both vector of tool tip orientation error $V_e$ and vector of tool tip position error $V_a$. This can be presented as a sum of vectors:

$$\overline{V}_s = \overline{V}_a + \overline{V}_e \tag{1}$$

The compensation mechanism in the decoupling method is composed of four stages:

- calculation of compensation angle in the A axis,
- calculation of compensation angle in the C axis,

- calculation of linear displacement resulting from compensation angles in A and C axes,
- calculation of total compensation values in three linear axes.

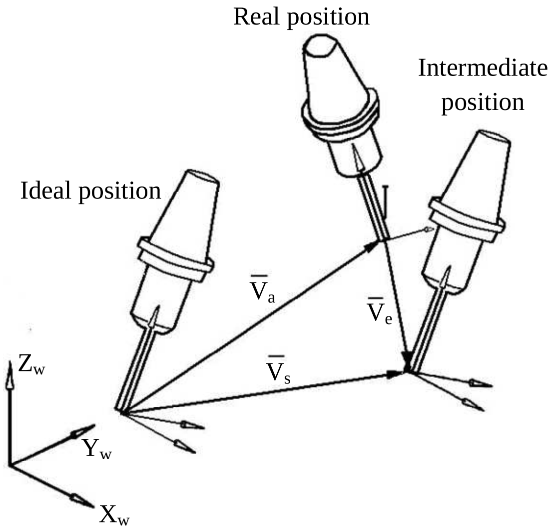

Fig. 13. Error compensation in decouple method [7]

The investigations of the decoupling method have been conducted on real machine tools in order to objectively assess its capability of reducing errors. Based on analyses, it was found that this compensation method can increase accuracy 8-10 times [7], but applies only to the geometrical error. Tests were conducted at maximum feeds of 10 mm/min and at small cutting forces.

## 4. INTEGRATED MACHINE TOOL THERMAL BEHAVIOUR MODEL FOR EFFICIENT ERROR COMPENSATION

Basic importance in thermal error compensation for machine tools has the elaboration of a very precise volumetric error model. Volumetric errors in working space can be determined in a precise way, based on an integrated thermal model of the entire machine tool, taking into account both internal heat sources and these resulting from the cutting process, as well as heat transmitted from the environment in natural operational conditions of the machine tool. General overview of this model is shown in Fig. 14. In this model, there is self acting heat propagation, generation of outputs for particular heat sources and change of thermal displacements, which are expressed by a volumetric thermal error in the controllable axes for each mutual position of tool in relation to the machined workpiece. Error model precision is defined by the precision of component models of single assemblies and their linkage in the calculation system.

Integrated model can be used in machine tool error compensation in order to:

- achieve precise identification of machine tool thermal behaviour at various external and internal influences,
- define volumetric errors in the entire work space in broad range of machine tool operational parameter changes and environment influences,
- determine the most suitable localisation of temperature measurement points and select their optimal, as low as possible, amount,
- test the accuracy of displacement compensation in any operational conditions.

Such model is very effective in error compensation, but its practical realisation is difficult. This difficulty is based on the need of integrating with a large, automated commercial dedicated software system, which simulates very precise models describing the behaviour of single assemblies. In order to realise such integration, simplifications are currently used which come down to applying thermal loads calculated by independent software. In this way, natural heat propagation is maintained, but there is lack of real-time feedback between heat losses and temperature distribution and deformations. Full integration can basically be achieved by means of a dedicated computation system, but from its nature it has many limitations, such as amount of discretisation elements and low discretisation automation which significantly decreases precision for modelling of large objects.

The coupling of dedicated programs with the integrated model shown in Fig. 14 is based on exchanging data between component models. Such type of integration applies mostly to a program for calculating machine tool motorspindles. In fact, two parallel models are created: integrated model of the entire machine tool and dedicated motorspindle model which precisely takes into account the conditions of generating heat in bearings in dependence on the type of bearing, rotational speed, load, lubrication conditions, material properties, assembly tolerances, environment conditions and bearing load conditions, as well as conditions of forced cooling in bearings and generating/carrying away heat in a drive motor. Thermal loads in bearings and in a drive motor, as well as heat admission coefficients connected to cooling of spindle bearings and a drive motor, precisely determined by a dedicated model, are input data for the integrated model. Thanks to this, integrated model acquires very precise data coming from the dedicated model. At the same time, the integrated model takes advantages of benefits coming from using commercial calculating system, that is the possibility of modelling geometrically complex large objects with consideration of all important assemblies of a complete machine tool, possibility of supporting with a CAD system during geometrical modelling, automatic generation of finite element mesh and very high speed of computations.

A method for increasing accuracy of thermal error modelling and their compensation, for complex structures of machine tools realising highly-variable and miscellaneous machining processes, is the utilisation of a dynamic and adaptive model [37]. The departure from the quasi-static model in the direction of the dynamic model allows much better representation of thermal phenomena taking place in machine tools for HSC. The connection of adaptive procedures with such model makes it possible to take into consideration many simultaneous changes of thermal error generation conditions in real-time. Therefore an attempt of building such model, described in paper [37] by Yang and Ni, deserves attention, despite its complexity and undoubtedly difficult application.

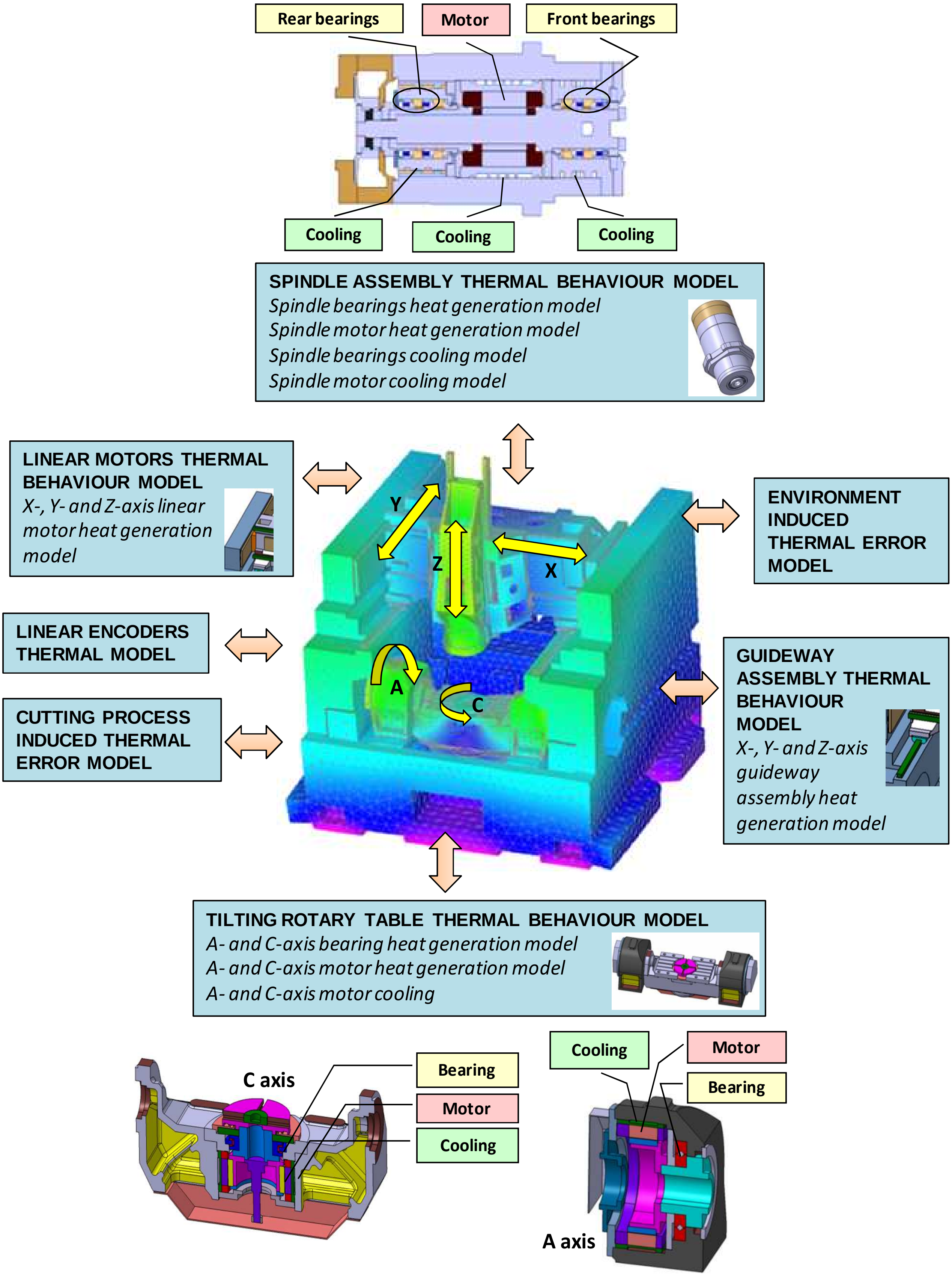

Fig. 14. Integrated high-speed 5-axis machine tool thermal operational behaviour model

## 5. CONCLUSIONS

Basic importance in error compensation has the elaboration of a very precise error model, which is usually a very complex task. Many error compensation methods have been elaborated which are applied in machining systems, but still they have not reached a satisfying accuracy level. The increase in operational accuracy of machine tools with the use of such methods amounts in 3 to 10 times. Particular compensation methods have however their limitations and their application may concern only selected cases.

Currently there are many investigations conducted, which are devoted to the perfection of compensation methods. Such activities are concentrated mainly on the following aspects:

- elaboration of a complex error model including thermal and geometric errors, as well as errors caused by cutting forces,
- development of error models which are reliable in changing operational conditions and for very complex structures of HSC machine tools,
- reduction of the amount of required sensors,
- optimisation of sensor location,
- improvement of reliability and error compensation system in a variable manufacturing environment,
- search for new, more intelligent and much more effective compensation methods compared to these applied currently, including these based on active measurements of some error components.

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