Journal of Machine Engineering, Vol. 8, No. 3, 2008

machining centre,
model, aerospace, precision

Jerzy JEDRZEJEWSKI[1]
Wojciech KWASNY[1]
Zbigniew KOWAL[1]
Wojciech MODRZYCKI[1]

PRECISE MODEL OF HSC MACHINING CENTRE FOR AEROSPACE PARTS MACHINING

This article shows the aspects of precise modelling of precise High-speed Machining Centres for High-Speed Cutting (HSC) of parts used in the aerospace industry. The main focus was made on the thermal errors having a dominant influence on the precision of machining. Main assumptions for a hybrid thermal model of a centre thermal behaviour have been stated, taking into account the characteristics of heat sources. On the example of a 3-axis machining centre, measured runs of heating up and heat displacements have been shown, compared to these determined with the use of simulations of a behaviour in assumed working conditions. A special attention was drawn to the phenomena taking place in motorspindles, as well as to the displacements of a spindle face during high rotational speeds of spindles and step changes of rotational speeds. The significance and influence of the bearing preload and centrifugal forces on the spindle axial displacements was shown, which is decisive on the precision of part machining. Additionally, it was shown that the important component of a machining error is an error of spindle position identification by means of a linear encoder, resulting from the thermal deformation of a centre body, to which a quartz linear encoder is fixed.

1. INTRODUCTION

The increase of the machining efficiency and the reduction of its costs while maintaining the required precision is decisive to the existence on a global market for many companies. This particularly applies to the present time period of a deepening economic crisis. For the manufacturers of machining centres, which are the basic means of highly efficient and flexible manufacturing of components in many branches of industry, this involves the need of the assurance of constantly raising precision of products, and at the same time lower costs, longer life-time and inexpensive exploitation. The need of fulfilling such rigorous requirements forces the use, in the design process, of new materials, innovative construction of many components as well as very versatile (complex) analyses based on behaviour models of machining centres in assumed working conditions. They need to take into account both changes of working conditions, as well as changes taking place in exploitation cycles and in the manufacturing environment. The changes of working

---

[1] Institute of Production Engineering and Automation, Wroclaw University of Technology, Wroclaw, Poland

conditions must be considered, which generate changing loads of a bearing structure of centres by static and dynamic forces, as well as by a heat load resulting from power losses, forced cooling, ambient temperature changes and heat created in the cutting process. In order to improve the design with such complex changing loads, it is essential to utilise the procedures of multi-criterion optimisation.

The whole load model of HSC centres is therefore very complex. It must be extremely precisely written mathematically and must consider the natural dynamics of single component loads and deformations resulting from them. Highly efficient and precise machining centres are machine tools with a very high rotational speed of spindles or motorspindles and with very high speeds of feed movements realised with the increased use of linear drives.

In the first case, motorspindle models must precisely consider the influence of centrifugal forces, while in the case of linear drives, the influence of inertial forces from the mass of headstocks and tables moved with high speeds together with machined parts.

The aim of the precise modelling is accurate identification of the behaviour of a machine tool in the state of changing loads and identification of disturbances in geometrical precision and working movements, which must be decreased to a possible minimum, and then compensated by a CNC system.

Effective compensation of errors requires, first of all, their minimisation and the utilisation of a model of these errors, acceptable in the currently accepted real-time compensation procedures. The rule is that single models undergo constant improvement and changes resulting from the advance in perfection of machining centre components – both hardware and software. The excellence of models is evaluated based on the conformity of calculation results, strictly speaking forecasting the behaviour of centres, with measurement results, e.g. temperature distribution or displacements and deformations. Measurement results of heating up and deformations of centre prototypes are also used to the model tuning process, so the simulation represents the real behaviour of a certain assembly or the entire machine tool as precisely as possible. It is therefore especially important for the measurement to include proper and precise information, and to ensure that no other are overlapping on the measurement result, distorting it. The skill and precision of a measurement, often underestimated, plays an enormous role here, equal to the precision of reconstructing physical phenomena in the model – load distribution, heat transfer and dynamics of modelled processes. In relation to spindle assemblies with very high rotational speeds, especially high precision of modelling and accuracy of measurements used to its verification is needed, because of high dynamics of loads and deformations [1-3]. Verification and tuning of a model must include such dynamics in a particularly precise way. In this process it is required to use the measurement systems independent from the machine tool. The measurement system of a machining centre is burdened with an excessive error, so without the knowledge of this error it is not suitable for model tuning.

2. CHARACTERISTIC OF A MACHINING CENTRE

The analysed precise machining centre is equipped with a bed made from epoxy concrete (see Fig. 1), a rigid and fixed cast iron table and a light, welded construction of a beam moved on two linear roller guides in Y axis. Another set of linear guides, fixed to the Y axis beam, is used to lead a steel, also welded, light cross slide. Relative to this slide, a headstock with a motorspindle has its movements along the Z axis, also on roller guides. Drives in all directions are linear with a forced motor cooling. The centre's working space, in which high precision of machining should be maintained, is shown in the right part of Fig. 1.

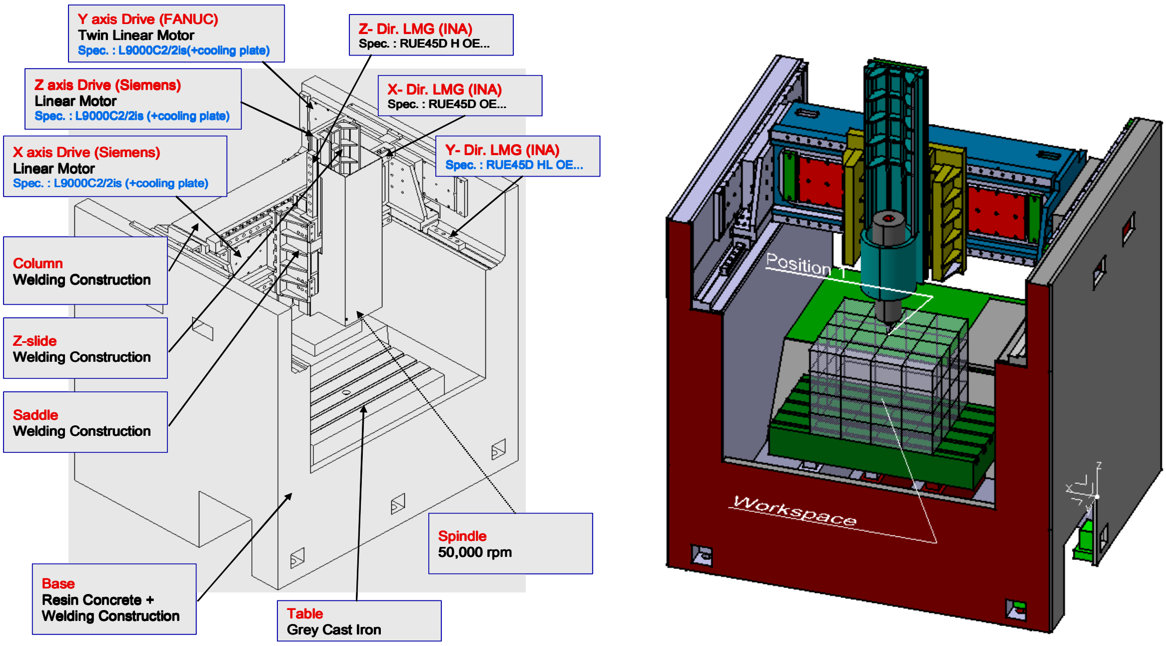


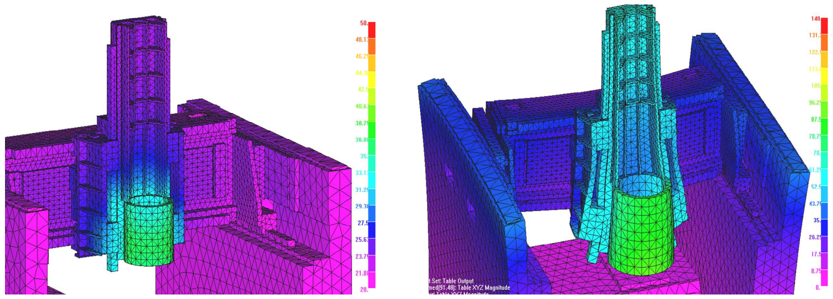
Fig.1. Machining centre structure

The measurement of axis movements is carried out by means of encoders with quartz linear scales. Main heat sources in a machining centre are: motorspindle motor, motorspindle bearings, linear drive motors and the environment – more precisely – ambient temperature changes.

The influence of motors and bearings on the temperature distribution on the carrying structure of a centre, can be seen in part a) of Fig. 2. As a result of such temperature distribution during maximum rotational speed of a spindle, 50.000 rpm, thermal deformations occur, which the thermal character, obtained from computer simulations, is shown on part b) of Fig. 2. It can be seen on it, that the bottom part of the bed with the large mass does not react on heat sources connected with drives. It will be however reacting with the suitable delay on the changes of the ambient temperature in the long-term cycle of these changes. The experimental investigations of the centre have shown, that already during changing cycle of speeds of the spindle reaching 20.000 rpm, displacements in the axis Z reach 100 μm in the direction of the table, meanwhile the displacement in the direction Y -

to the servicing row 30 µm, considering the fact, that the measurements were conducted at the central position of the spindle.

In the area of a headstock, especially near the bearings, large and intensive temperature changes are observed, while slow and small temperature increments are observed on the housing of a bed. In a multi-day time cycle it is observed that in the environment of an idle centre – without supplying the energy to the motors of rotations and feeds – ambient temperature changes appeared, with magnitude of over +2 °C to –1.5 °C from the initial state. Such changes in the Z axis resulted with the displacements of a spindle by around +4 µm (in the direction to the table) and around –12 µm vertically up. Despite the use of epoxy concrete for the supporting structure of a bed, it is characterised by the large sensitivity to the ambient temperature changes. Induced thermal displacements must be compensated. Corresponding simulation research shown that such type of the spindle displacements in the Z axis can be modelled with the precision of 2 – 3 µm (divergence between the model and the measurement).



a) **Temperature distribution [^{o}C]** b) **Thermal deformation [µm]**

Fig. 2. Temperature distribution a) and thermal deformation b) of the machining centre (50,000 rpm, steady state, ambient temperature 20°C, oil cooling – 1,5 l/min, idle run)

It is more difficult to model the axial displacements of a centre's spindle in movement conditions, especially during large changes of rotational speeds (Fig. 3).

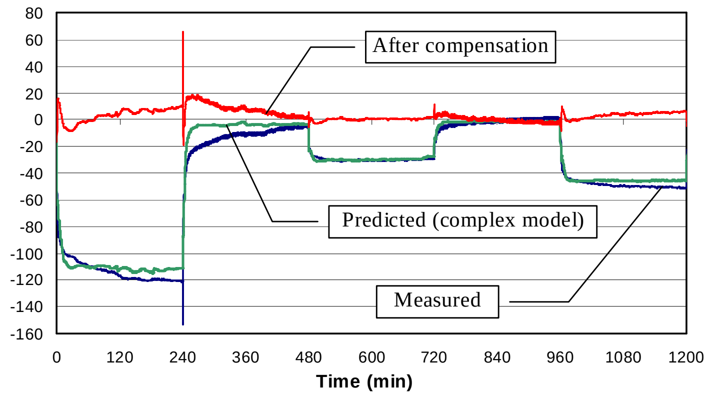


Fig. 3. Accuracy of predicting machining errors during variable cycle of operation of vertical machining centre by means of integrated model

Recorded runs of such displacements clearly visualise irregular and sudden displacements in the moments of rotational speed changes, as well as regular and relatively slow displacement resulting from thermal displacements, taking place during the operation of spindle with a fixed rotational speed. The large fineness of the possessed computational model is proven by the possibility of modelling the distortions of measurement results, which are identified by their excessive irregularities. Fig. 3 shows the displacements of the centre's spindle, both measured and forecasted with the use of a computational model.

Large dynamics of displacements during rotational speed changes is visible, not precisely enough rendered by the computational model and requiring specific explanation – by means of recording with high sampling frequencies and precise theoretical description.

3. GENERAL CHARACTERISTIC OF A THERMAL COMPUTATIONAL MODEL FOR SPINDLE UNITS

In order to ensure high precision of the thermal model of the spindle unit's behaviour, considered to be the main source of thermal errors in a machining centre, such model must fulfil many fundamental requirements. The model must reproduce natural thermal loads. This requires the reproduction of real-time power losses generation, taking into account varying loads of the motorspindle motor with torque, loading of motorspindle bearings with internal and external loads, as well as loads with the friction moment [4]. Therefore the entire complex of factors and phenomena influencing the power losses in bearings must be considered (see Fig. 4). Additionally, the model must take into account as precisely as possible the conditions of heat transfer in the area of a spindle unit and its outside environment, as well as in the entire area of headstock housing [5].

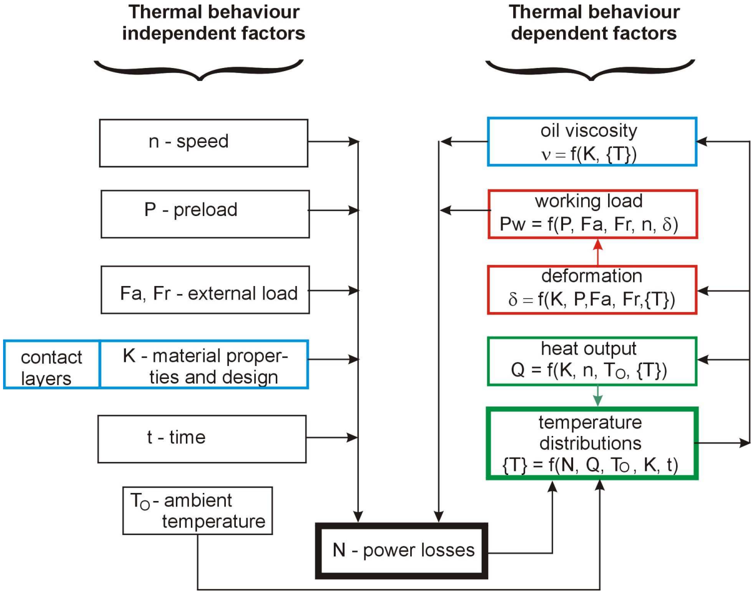


Fig. 4. Interrelations between factors affecting power losses in spindle bearing units

In the modelling of a machine tool realising the machining process, the influence of such process must also be considered, both from the point of view of loading by cutting forces and of the heat generated in the cutting zone together with the impact of the cooling medium and chips.

The model, elaborated and applied by the authors, is a hybrid model, integrating finite element method (FEM) and finite difference method (FDM). All cylindrical elements of the assembly are modelled with the use of FDM, while the rest, such as the housing of a headstock and other housings, with the use of FEM. This ensures high precision of modelling internal loads and deformations of a spindle unit [6]. A general diagram of such model is shown on Fig. 5. The influence of the hydraulic cylinder used for tool fixing is also considered in this model. Four groups of input data are distinguished, which apply to: construction, working conditions of the unit, realised machining process and the influence of the environment. Output data are: axial shift of a spindle and thermal displacement.

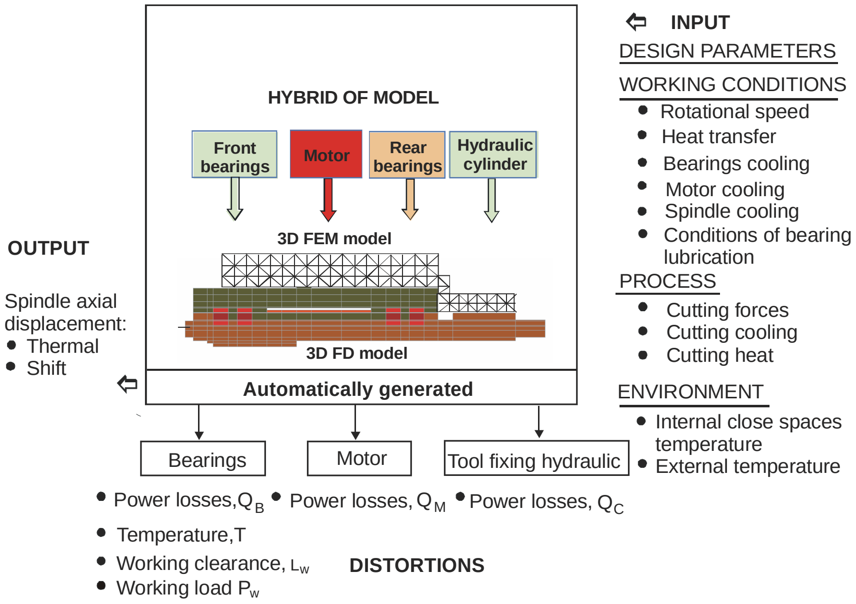


Fig. 5. Spindle unit thermal model

The discussed model integrates a series of partial models of thermal phenomena taking place in the area of the unit, as well as phenomena concerning the distribution of internal and external forces. These models are, for example, used for:

- calculations of the amount of heat generated in ball bearings
- heat flow in the bearing unit
- forced cooling of spindle bearings
- calculations of the amount of heat generated in a motor and the distribution of such heat to a stator and rotor
- stator cooling
- cooling of spindle from the inside
- determining the internal forces in bearings and the axial shift of a spindle

In order to make sure that the model reproduces the behaviour of a spindle unit and the entire machining centre during its operation, it must describe, in real-time, runs of load changes, power losses, deformations and displacements of the components and working units with natural connections and mutual interactions between them. Therefore the precision of partial models has a decisive influence on the conformity of calculation results with a properly conducted experiment (measurement).

Main procedures for calculating the distributions of temperatures and displacements are shown on Fig. 6. Different variants of the bearings' preload are also shown on this figure.

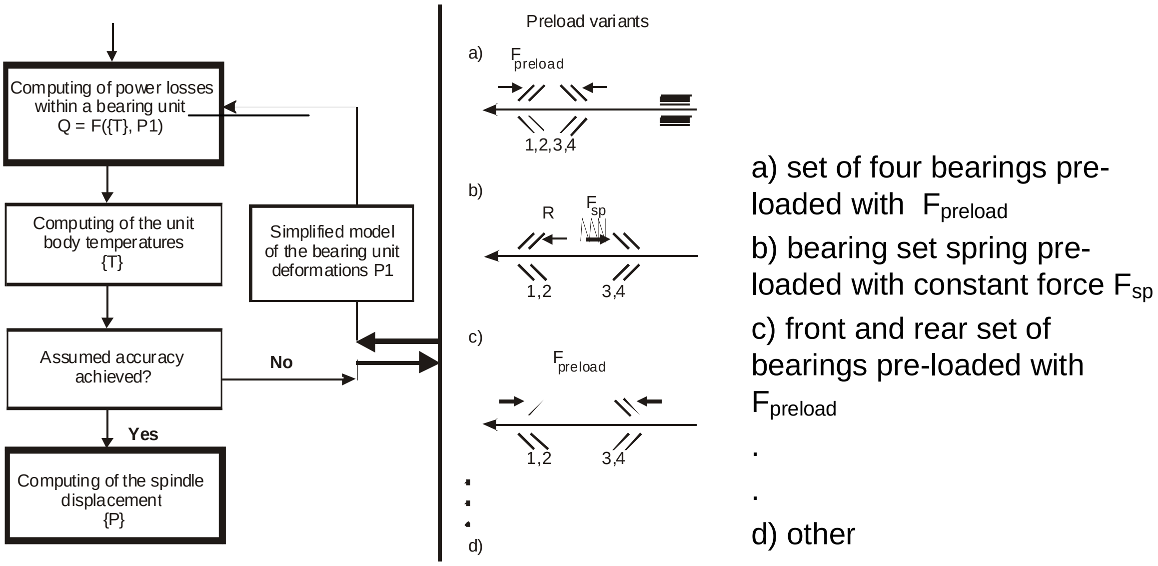


Fig. 6. Procedure of determining the temperature and thermal displacement

A widely chosen variant by the constructors of spindle units is variant b, in which the preload of bearings is realised by means of a spring or hydraulic actuators. A precisely operating actuator can be a piezoelectric one, which however is very costly because of the high cost of a piezoelectric material and the high complexity of its power supply. Among such variants, preloading by means of a spring is most widely used, considered to be an inexpensive and simple constructional solution. However, the selection of springs and their force should result from the analysis of the required stiffness of a bearings unit in working conditions of a spindle assembly. Therefore a suitable computational model must be available. Initial behaviour of a spindle bearings unit is determined by their preload P (see Fig. 4) and the load of every bearing (bearing pair), $F_{a\ 1,2} = f\ (P)$ in the post-assembly state. The engagement of rotation initiates power losses, heating of a spindle assembly, thermal deformation S_T and the generation of a corresponding force F_T, which increases loads $F_a = f\ (P, F_T)$. The appearance of the external load A leads to the further increase in the load of a bearing $F_a = f\ (P, F_T, A)$. Simultaneously, a load from centrifugal forces, F_C, appear and the resulting load $F_a = f\ (P, F_T, A, F_C)$. For every load state, a state of equilibrium is created in a bearing unit. In a computational model it is a rule that if such force equilibrium is disturbed in a spindle unit, the computational program searches for and determines equilibrium conditions, altering a relative location of bearing rings or values of internal forces – as it would take place autogenously in real working conditions of a bearing unit.

For every load state of a spindle unit a defined state of thermal equilibrium (momentary), which is defined by the balance of heat fluxes.

Equilibrium of heat fluxes at node “i” of a division mesh was determined according to the relationship:

$$\sum_{w=1}^{W\,\max} QP_{i,w}^{h+1} + QZ_i^{h+1} - QS_i^{h+1} = QA_i^{h+1,h} \tag{1}$$

and the initial condition $T_i^{h=0} = TP_i$

where:

$QP_{i,w}$ - flux of heat flowing between nodes “i” and “w” of a mesh. Summation extends over fluxes to all “Wmax” neighbouring nodes,

QZ_i - flux of heat transferred from a heat source to n ode “i”,

QS_i - flux of heat exchanged between a surface encompassing node “i” and the surroundings. A variety of modes of heat exchange over the machine tool body considered in the system are shown in Fig. 7 ,

QA_i - flux of heat accumulated in material encompassing node “i”,

h,h+1 - indexes denoting heat flux at time instant “h” or its successor “h+1”,

TP_i - temperature of node “i” at an initial time of thermal process; h=0.

In addition to the above elements of division another group of spatial elements was adopted to represent either closed cavities of the body or spaces filled with coolant.

In order to determine the heat flaxes it is necessary to recognize a temperature difference between modal temperature and neighbourhood temperature and an equivalent coefficient of heat transfer concerning: heat transfer in joints, free convection forced convection, radiation convection inside a body, covered space and so on. A forced heat exchange model uses heat balance equations for the unsteady heat transfer description between the circulating coolant and the cooler’s surface. The basic components of the model of forced cooling machining centre units – basically spindle unit shows Fig. 7.

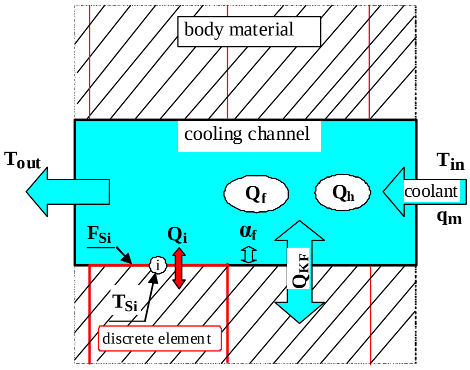


Fig. 7. Heat fluxes in cooler channel

4. OPERATIONAL BEHAVIOUR OF SPINDLE UNIT

The source of impetus for a detailed analysis of the behaviour of a HSC spindle unit were the results of studies on the prototype of a centre with the rotational speed of a spindle reaching 50.000 rpm. Such studies shown that during changes of the rotational speed, large shifts of a spindle appear, not observed in headstocks with low rotational speeds. The similar behaviour of a spindle is also observed in the paper [7]. In order to explain such behaviour measurement experiments with high sampling frequencies were conducted, well identifying the behaviour of a spindle tip during changes of the spindle’s rotational speed according to the previously defined cycle of speed changes.

The results of testing the behaviour of a spindle during rotational speed changes are shown on Fig. 8 [8]. On this figure, black line represents a run of spindle displacement as a function of time. Both regular changes resulting from thermal elongations of a spindle and sudden shifts of the value appearing in the moments of the rotational speed changes are

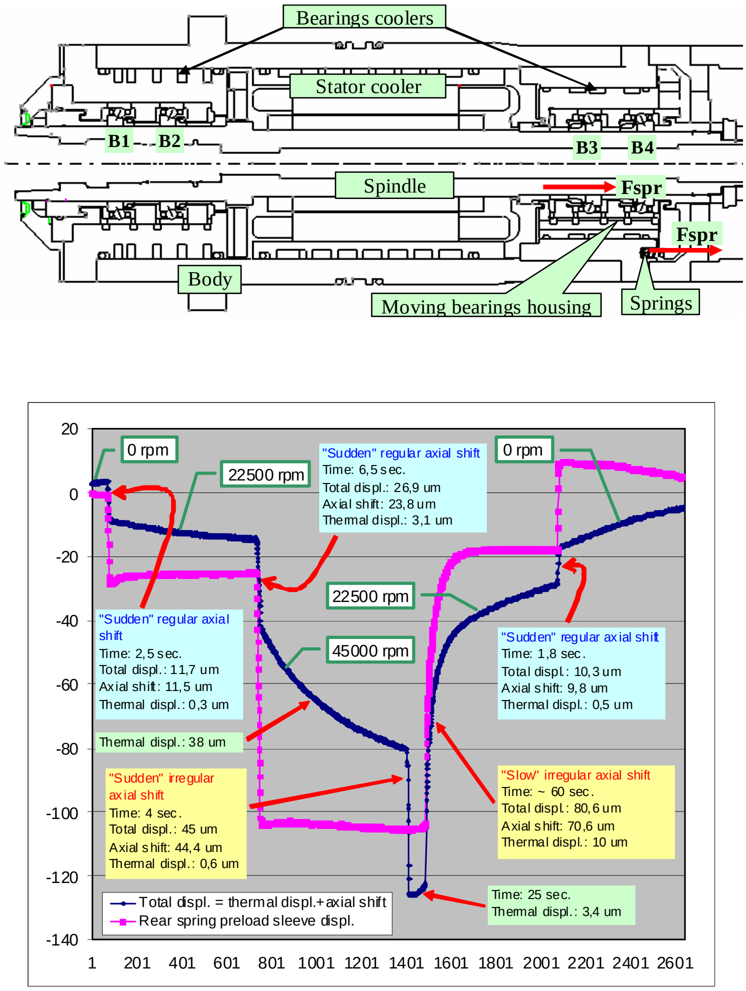


Fig. 8. HS machining centre spindle shift with overlapping thermal elongation, and sleeve movement analysis

visible on the figure. Red line represents recorded displacements of a bearing loading sleeve. In the investigated constructional solution of the motorspindle, the loading of bearing is realised by means of a moving sleeve and springs. The task of a moving sleeve is to compensate thermal elongations of a spindle, to maintain the required load of bearings and to ensure rigid support of front bearings in the axial direction.

The starting moment of a test, that is the engagement of rotational speed of 22.500 rpm, a sudden shift of the displacement value is visible on the graph, from zero to 11,5 µm. In the further part of the graph, a slow growth of displacements is visible, representing thermal elongations of a spindle. A much larger shift took place in the moment of increasing rotational speed to 45.000 rpm, after which a very intensive thermal elongation of a spindle took place. After decreasing rotational speed to 22.500 rpm the spindle, instead of returning to the initial state, suddenly dropped almost 45 µm. It was not until 25 sec from the moment of increasing rotations when a sudden decrease of the spindle displacements was visible. In the further period of a measurement cycle a slow cooling is visible, followed by a consecutive spindle shift after stopping the machine tool and a consecutive period of slow cooling.

As it was already mentioned, in angular roller bearings centrifugal forces acting on balls cause the relocation of contact points of a ball with raceways and the contact angle of a ball relative to the outer and inner raceways. This results with the change of bearing’s axial stiffness and every time a new, different state of force and moment equilibrium is settled [9]. Besides the spring force, balls are also loaded by a centrifugal force, which causes pressing of the balls into a slot between both rings, while the values of pressure of balls on the inner and outer bearing ring must ensure the equilibrium of forces in a bearing.

For the analysed construction, axial movements of a spindle are strictly connected to the movements of a loading sleeve during the changes in rotational speed. It is because the displacement of a spindle’s tip consist of the following: displacement of a sleeve ensuring the equilibrium of forces in bearings, displacement of a sleeve caused by the shortening of a fast-rotating spindle and displacement of the shortening of a fast-rotating spindle.

The use of a precise model of the behaviour of a spindle assembly allows analysing and forecasting the changes of spindle tip position changes in operating conditions with a high accuracy.

By observing the movements of a moving sleeve (red line) it is possible to claim that during the entire test the sleeve does not fulfil its basic function, which is compensating thermal displacements. It only reacted to the changes in rotational speed of a spindle, and not always correctly, which is signified by the delayed, by 25 sec, sleeve reaction to the decrease of rotational speed from 45.000 rpm to 22.500 rpm.

In order to make sure that the rear bearing node is constantly effectively loaded, the sleeve, to which the force of a spring is applied, should be able to slide freely in a housing. If the movement resistances of such sleeve are too big, it will not react properly.

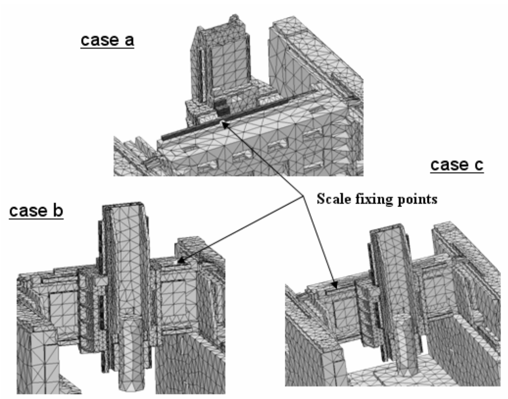
With a properly operating moving sleeve or a sleeve led by rolling elements, operating with no jamming and reaction delays, thermal elongations of a spindle would not be visible on a graph from measurements (sleeve movements should compensate them in a large degree), as well as the phenomenon of a falling spindle would not be observed, while the sleeve returning without delay would prevent this happening.

5. MACHINING CENTRE MEASURING SYSTEM OPERATIONAL BEHAVIOUR

If it is desired to effectively compensate the distortions of machining centre precision in their operating conditions, one should not omit the errors introduced by the distance measuring system of working units in controllable axes. The manufacturers of CNC machine tools using such systems have a choice between quartz linear scales with a lower thermal expansiveness coefficient and steel linear scales, which coefficient is conforming to the coefficient of the material used for housing to which the scale is fixed.

By choosing the quartz scale it is necessary to choose the location of its fixing. It has three fixing holes – two at the ends and one in the middle. During operation the bodies of a centre, e.g. a beam or a bed, to which the scales are fixed, undergo thermal deformations. Such deformations cause the linear scale to be displaced together with its fixing points.

In a centre shown on Fig. 9a beam is rigidly bound with a right guideway by means of two spaced clearance-free rolling blocks. Rolling blocks on the left guide play only the role of a moving support. Elongations of a beam during operation are a function of heat fluxes acting on it, mainly from linear motors and the environment. They cause the displacement of a headstock fixed to a beam in the X axis direction.



Effect of straightedge fixing location on measuring error:
case a) - central point fixing and glass scale moved to the right side
case b) - factory position and fixing point moved to the right side of glass scale
case c) - factory position and fixing point moved to the left side of glass scale

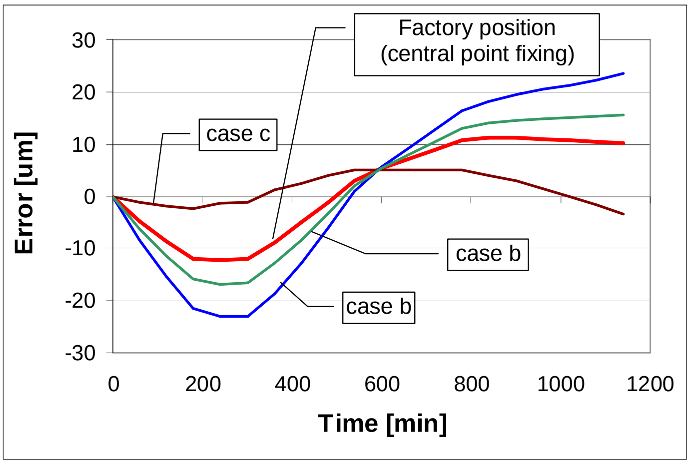


Fig. 9. Positioning effect of glass scale in machine tool structure [10]

The location of a headstock in the X axis is also influenced by thermal deformations of a machine bed. Deformation of a body displaces the point beam support to the right, i.e. in the direction opposite to thermal elongations of a beam. Glass linear scale is bound with a beam by means of an aluminium housing. Thermal expansiveness of such housing does not influence the measurement error of the location of a headstock only when the housing is fixed to the beam in the middle of its length, and the glass scale is also fixed with the housing in the middle of its length. If the housing is fixed to the beam in any other location, then the thermal dimensional changes of a housing will influence the error of headstock positioning. A component of positioning error, while the headstock location is other than central, will also be thermal elongations of the linear scale itself, which thermal expansiveness coefficient usually averages at around $8*10^{-6}$ 1/K.

Headstock positioning error model, taking into consideration different locations of a beam, is very complex and difficult to define with a required precision, because of frequent, or even constant location changes of a headstock.

In order to distinguish the influence of the linear scale housing fixing point to the beam, a computer simulation was carried out, in which fixing in the middle point and in two extreme points was considered (Fig. 9). In all three cases it was assumed that the glass scale was fixed to its aluminium housing in the middle point of their lengths. The model takes into consideration the elongations of a beam and a linear scale with its housing, as well as thermal deformation of the entire structure of a machine tool in a function of ambient temperature changes. It can be concluded from the simulations that dependent on the fixing point of the glass scale housing to a bed the positioning error may even differ by 10 μm, and large values of such errors signify the need of their minimisation and compensation.

6. CONCLUSIONS

The internal tension of bearings in a high speed spindle units is very complex. Precise identification of a high speed bearing unit and forecasting of their life cycle requires detailed model recognition of complex loads. In the decrease of high speed spindle units heating up and axial thermal displacements the significant role play bearing rotating elements torque, value material parameters and intensity of external cooling. For decreasing of shift it is necessary to keep the bearings tension in whole range of speed changes. Spindle positioning precision depends on glass scale of linear encoder design, fixing design and fixing point location.

ACKNOWLEDGEMENT

The authors express the best thanks to Doosan Infracore Co for permission for use of result of research investigations of machining centre and EU Commission IP AFFIX founder and to the Ministry of Science and Higher Education.

REFERENCES

[1] ALTINTAS Y., CAO Y., *Virtual design and optimization of machine tool spindles*, Annals of CIRP, 2005, 54/1, 379–382.

[2] JEDRZEJEWSKI J., KOWAL Z., KWASNY W., MODRZYCKI W., *Hybrid Model of High Speed machining Centre Headstock*, Annals of the CIRP, 2004, 53/1, 285-288.

[3] MORIWAKI T., SHAMOTO E., *Analysis of thermal deformations of an ulltraprecision air spindle system*. Annals of the CIRP 47./1, 1998, 315-319.

[4] WINIARSKI Z. KOWAL Z., *Investigation of the effects of heat generation in HSM electro headstocks*, Journal of Machine Engineering, 2006, 6/2, 107-115.

[5] JEDRZEJEWSKI J., *Effect of the Thermal Contact Resistance on the Thermal Behaviour of the Spindle Radial Bearings*, International Journal Machine Tools Manufacturing, 1988, 28/4, 409-416.

[6] JEDRZEJEWSKI J., KWASNY W., KOWAL Z., MODRZYCKI W., *Operational behaviour of high speed spindle unit*, MM Science Journal, October 2008, 3, 40-43.

[7] WECK M., SPACHTHOLZ G., *3- and 4-Contact Point Spindle Bearing – A New Approach for High Speed Spindle Systems*, Annals of the CIRP, 2003, 52/1, 311-316.

[8] JEDRZEJEWSKI J., KWASNY W., MODRZYCKI W., *Limiting precision distortions in spindle unit of HSC machining centre*, Journal of Machine Engineering, 2008, 8/1, 44-53.

[9] CHEN J.-S., HWANG Y.-W., *Centrifugal force induced dynamics of a motorized high-speed spindle*, Int J Adv Manuf Technol, 2006, 30, 10–19.

[10] JEDRZEJEWSKI J., KOWAL Z., KWASNY W., WINIARSKI Z., *Precise modelling of HSC machine tool thermal behaviour*, Journal of Achievements in Materials and Manufacturing Engineering, 2007, 24/1, 245-252.