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Precise modelling of HSC machine tool thermal behaviour

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Analysis and modelling

ABSTRACT

Purpose: The development of precision machine tools requires modelling, simulation and optimization, especially the accurate modelling of machine tool thermal behaviour aimed at improving the machine tool design.
Design/methodology/approach: This paper discusses machine tool design improvement based on thermal behaviour modelling and the complexities involved. A highly accurate thermal model of the HSC machine tool is presented and the necessity of including the whole complex of factors affecting machine tool behaviour and error compensation is highlighted. Modelling problems are illustrated with examples of accurate modelling and simulation of machine tool behaviour, aimed at minimizing thermal disturbances in machining precision.
Findings: The precise modelling of HSC machine tools dynamic spindle displacement during a change of rotational speed.
Research limitations/implications: The transitional states of spindle speed changes are very complex and difficult to precise recognition.
Practical implications: The need of integrated complex modelling of precise HSC machine tools thermal behaviour.
Originality/value: All models used for machine tool behaviour simulation are fully original.
Keywords: Manufacturing; Machine tool; Modelling; Thermal behaviour

1. Introduction

The constant increase in spindle speeds and feed motions of machine tool assemblies entails higher and dynamically changing power losses. As a result, the precision of machine tools and their operations is affected by the generated heat and its accumulation in the machine tool structure and by the heat transmission conditions. In order to reduce the effect of thermal phenomena on machining precision it is necessary to seek solutions already at the machine tool design stage through the precise modelling, simulation and optimization of machine tool thermal behaviour, ensuring minimum thermal displacements of the work assemblies in normal operating conditions, i.e. during the machining of workpieces. During normal operation the machining precision is affected by the thermal phenomena occurring within the machine tool structure as well as the ones associated with the machining process and the environment (the machine tool's operating environment) [1,2,3,4,5,6].

In order to be able to effectively prevent thermal disturbances in machining precision it is necessary to very accurately model the machine tool's thermal behaviour (including all the disturbances and their entire occurrence dynamics) and the physical thermal phenomena themselves. For this purpose IT tools which allow one to accurately model and simulate the machine tool's behaviour in real time are indispensable.

The real time requirement is particularly important in the case of tool spindles since their displacements must be dynamically compensated. Thermal problems in high-speed precision machine tools are not limited to structural and parametric optimization. The machine tool becomes ever more autonomous, incorporating measurement functions and work parameter and operating precision self-adjustment in an increasingly more intelligent way [9,10,11,12].

The incorporation of measurement functions in the machine tool in which thermal disturbances occur means that the functions' accuracy must be increased and be subject to verification. Consequently, simulation analyses of machine tool behaviour must be very precise, commensurately with the precision of the measuring devices. Unfortunately, there are no effective methods of measuring machine tool volumetric errors in motion conditions during normal operation. In practice, probably the only effective method of evaluating precision are workmanship accuracy measurements performed on test workpieces.

This paper provides several examples of the accurate modelling and simulation of machine tool behaviour, aimed at minimizing thermal disturbances in machining precision.

2. Aims and criteria of modelling

A model of the behaviour of a machine tool in its natural environment and operating conditions is usually dedicated to the realization of one of the following goals:

- analysis of the potential for increasing machine tool precision, for which all the phenomena involved, particularly the thermal ones, must be very accurately mapped;
- optimization of machine tool behaviour, for which a large number of objective function computations must be performed in real time and so the model needs to be somewhat simplified;
- real-time error compensation in the whole machine tool work space and so a simple model, but aided with signals from proper sensors (e.g. temperature sensors for thermal error compensation) is required;
- correction of machine tool behaviour, particularly machine tool behaviour correction control, which in many cases must be based on a hybrid (mechatronic) model (owing to the development of the microelectronics and actuators employed in machine tools, the importance of such modelling has significantly increased).

Machine tool designers should ensure (among others):

- proper machine tool precision (which steadily increases but is difficult to achieve);
- long machine tool lifetime, with regard to both precision and effectiveness;
- high flexibility, which has many forms and covers process hybridity;
- short lead time;
- low cost of the machine tool and its operation (today this can be modelled).

It is not difficult to notice that because of their contradictory nature all the above requirements cannot be satisfied at the same time, and certainly not through conventional optimization. Therefore a compromise (negotiation) is necessary.

The solution of thermal problems significantly contributes to both increasing the precision of machine tools and machining processes and satisfying the other machine tool improvement criteria.

3. Importance of environmental factors

Typical production machine tools, such as machining centres, are operated in different shop floor conditions. The ambient temperature varies and changes widely and so does the machine tool's geometry. The changes become superimposed on changes in geometry caused by the heat sources distributed inside the machine tool structure and the ones originating from the machining process. In order to ensure the replicability of workpiece dimensions in long (e.g. lasting many hours) machining cycles the machine tool geometry should be little sensitive to ambient temperature variation.

Depending on the heat capacity of the particular machine tool load-bearing components, such as main bodies and sliding assemblies, their temperature changes with a certain delay relative to variation in ambient temperature. For example, in a lathe centre operating in a repeatable cycle the spindle motor bearer reaches a minimum temperature with a delay of 120 min relative to the minimum ambient temperature, the support's lower part near the rolling screw bearing set with a delay of 260 min and in the case of spindle displacement (the machining error) the delay amounts to 440 min (Figure 1). The time cycles of the changes are the same, i.e. they correspond to the changes in ambient temperature. Depending on the season and the temperature control in the production rooms the temperature can change from a few to twenty degrees Celsius, resulting in spindle displacements up to tens of μm. If its values are significant, the above error should be taken into account in the overall thermal error compensation. Thus the accuracy with which the error is modelled is highly important in this case [7,8,9,13].

The graph shown in Figure 2 illustrates the influence of ambient temperature variation on machining centre spindle displacements against the background of the measured values. Despite the high model precision, the mapping error at times exceeds 2 μm. Nevertheless the courses of the curves are very similar.

4. Modelling machine tool with regard to heat accumulation due to presence of guards

The modelling of machine tool thermal behaviour generally begins with the modelling of the load-bearing structure whereby the model can be easily verified. In order to evaluate the thermal behaviour of a machine tool in its operating conditions it is necessary to take into account all the body, machining zone, guide, rolling screw and other guards and the spaces they enclose and the fact that heat accumulates in them whereby the actual temperatures of the guarded assemblies are higher, affecting the machine tool's thermal displacements.

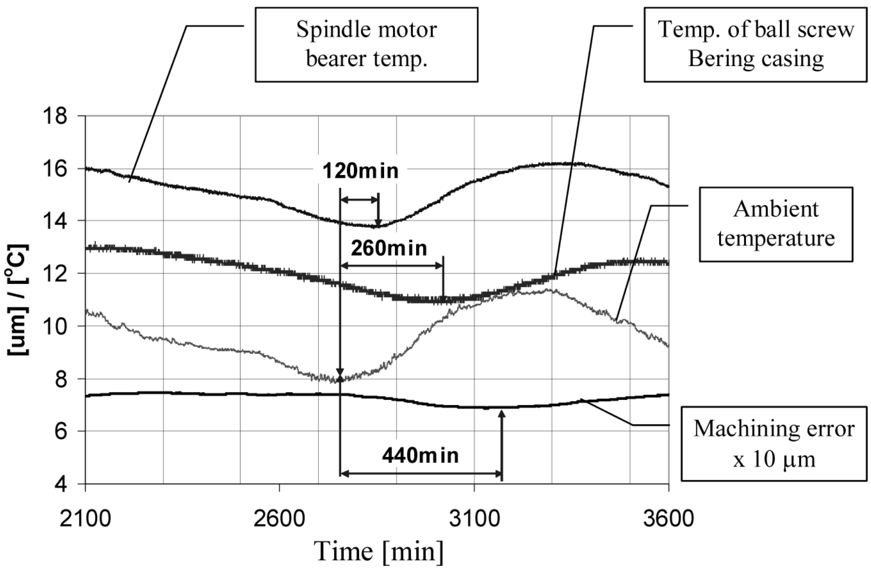


Fig. 1. Variation in temperature of lathe centre assemblies and in machining error, due to twenty-four hour fluctuations in ambient temperature

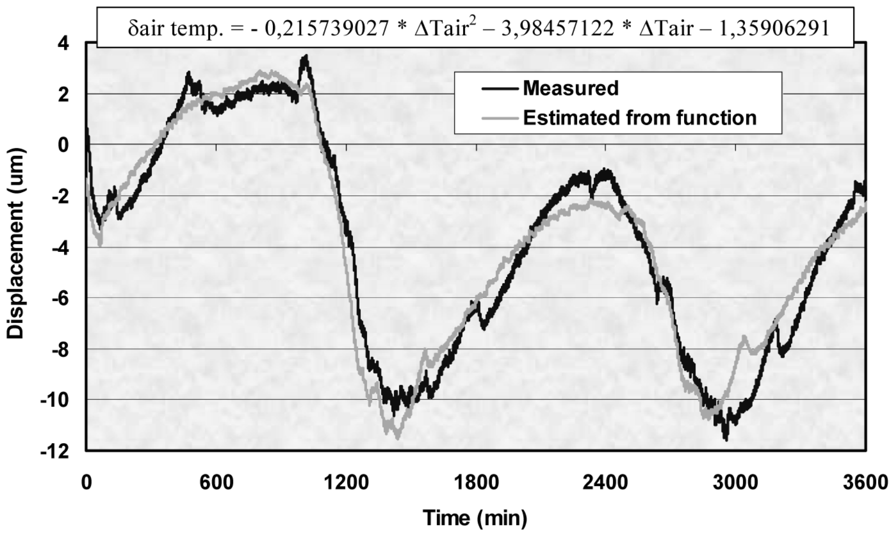


Fig. 2. Mappings of effect of ambient temperature variation on machining centre displacement

Figure 3 shows the effect of covers on the thermal displacements of a lathe centre spindle. When first the headstock cover (version B) and then in addition the work space cover (version C) are taken into account, the displacements are considerably larger than the ones for the load-bearing structure alone. The higher the level to which the machine tool heats up, the longer its thermal stabilization, as clearly evidenced in Figure 4 showing spindle displacements along axis Z (the spindle axis). It is clearly apparent that if the model does not take into account the effect of all the principal covers, the machine tool thermal behaviour is evaluated with a large error and the model is inadequate for predicting thermal errors for error compensation.

5. Modelling phenomena in bearing sets of high-speed spindles

Accurate modelling of the thermal behaviour of high-speed spindle assemblies is vital for the evaluation and optimization of their operating conditions and for the development of HSC machine tools in general.

As the rotational speed of the bearing increases so does the rotational force acting on the balls and the contact angle of the bearing changes as shown in Figure 5. As the bearing contact angle decreases the bearings are relieved. The load relief should be compensated by the spring force in order to maintain the required rigidity. The accuracy with which these dynamic phenomena are modelled affects the whole modelling of thermal phenomena in the bearings. In order to verify the developed models the thermal displacement component stemming from the total displacements measured during the continuous operation of the machining centre (Figure 6) was removed. The remaining part represents only the spindle displacements which occur during a change in rotational speed, caused by changes in the bearing contact angle and in the deflection of the tension springs. It was difficult to precisely determine the impact of the thermal component during spindle acceleration up to a set rotational speed, which undoubtedly affects the accuracy of the experimental verification of the dynamic calculation models.

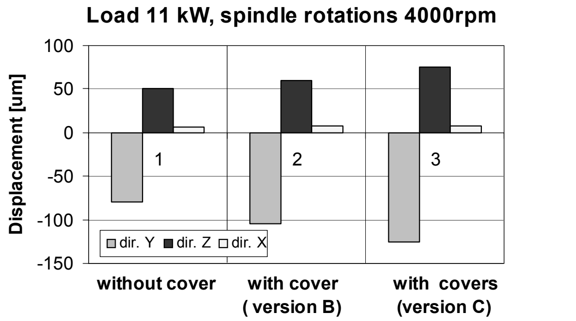


Fig. 3. Effect of headstock guard (version B) and in addition, of work space cover (version C) on thermal displacements of lathe centre spindle

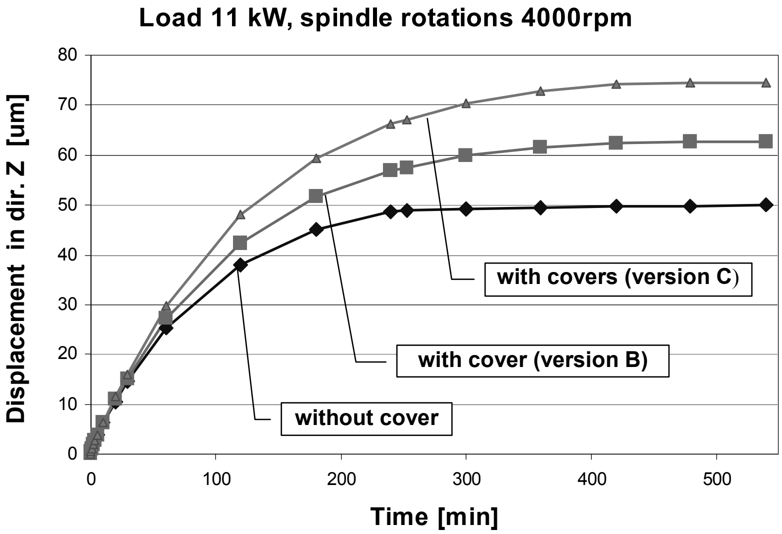


Fig. 4. Effect of covers on level and time of lathe centre model thermal stabilization

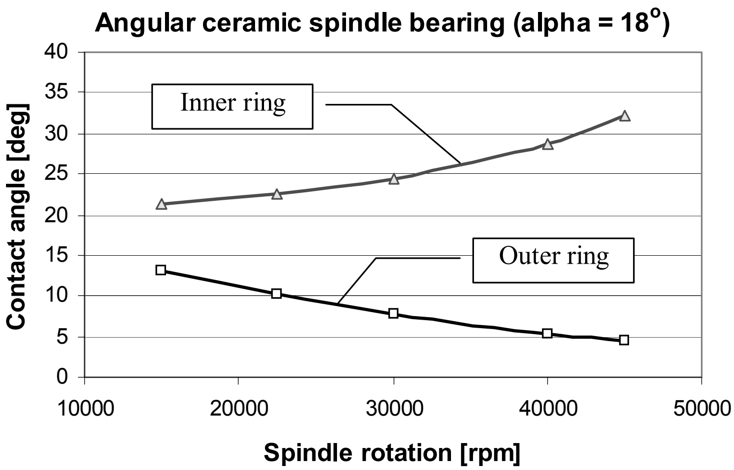


Fig. 5. Effect of rotational speed on bearing contact angles in high-speed spindle bearing with hole 50 mm in diameter

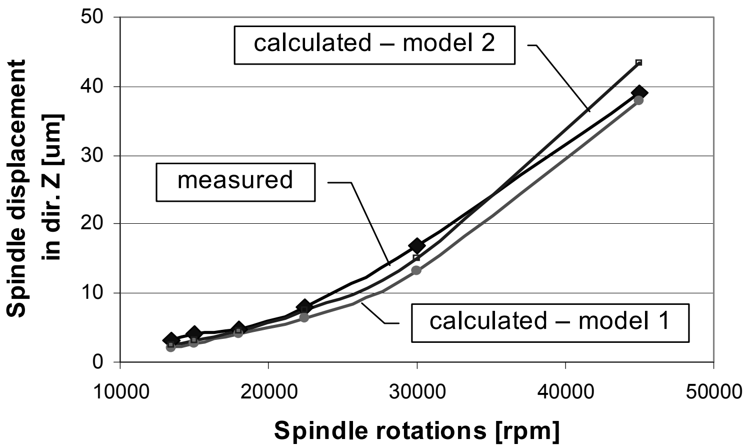
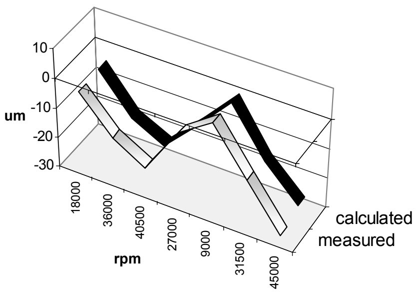


Fig. 6. Verification of models describing phenomena typical for high-speed bearings

A variable cycle of operation of the centre was simulated using model 2. After each change of rotational speed the new spindle positions were determined. In Figure 7 they are compared with experimental results (with the thermal component removed). The figure shows that even for such a complex cycle as the assumed one the model performs well. The difference of a few micrometers at a change in speed from 45000 rpm to 27000 rpm is due to the model's small imperfection as a result of which the results for 45000 rpm are overstated and the ones for 27000 rpm are understated (Figure 6).



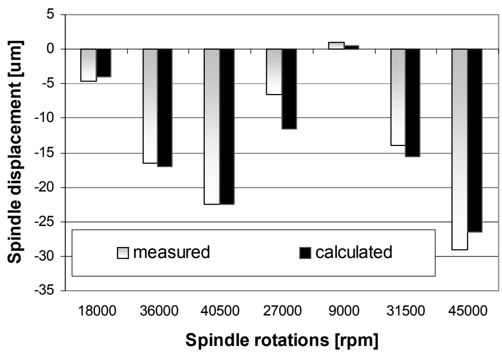


Fig. 7. Simulation of variable cycle of machining centre operation

In order to compensate their effect on machining precision the spindle displacements which occur during changes in speed and the thermal displacements must be known.

The fact that the temperature distribution in the electrospindle bearing set is very complicated makes it difficult to precisely determine the thermal displacements. The temperatures vary considerably both along the outer bearing casing and above the cooling jacket, an much more along the spindle and the inner races (Figure 8). This means that the distribution of thermal deformations along the inner and outer bearing casings and in the bearings themselves is also very complicated. This undoubtedly affects the smoothness of tightening the bearings during changes in the contact angle.

The actual performance of the electrospindle for long operating periods at set speeds and their changes is shown in Figure 9 which was used to evaluate the displacement compensation ability on the basis of displacements predicted by numerical calculations and approximations, by means of two models: separately for spindle displacements at speed changes and separately for thermal displacements.

The results of approximation by a function integrating dynamic spindle displacements and thermal displacements are shown in Figure 10. The latter model reflects much better in sure areas the courses of the measured displacements. In this case the distribution of the error of the predicted displacement compensation is almost acceptable.

6. Modelling of effect of mounting locations of quartz straightedges

Quartz straightedges for measuring the distance of CNC machine tool sliding components are characterized by a very low thermal expansion coefficient α (C.T.E) – in the order of 8 μm/m °C. The thermal expansion of the cast-iron bed body or the beam is 12 μm/m °C. As the ambient temperature and that of the body change the straightedge deforms (elongates) and shifts together with the thermal displacement of its point of support. At a fixed position of the slidable headstock body the control system ensures its fixed position relative the straightedge. But the latter shifts as the ambient (body) temperature changes, and consequently generates a measuring error. The value of this error and its correlations with the position of the straightedge, the position of the point at which the straightedge is fixed to the body and the position of the headstock along the direction in which it moves are of interest to the machine tool designer.

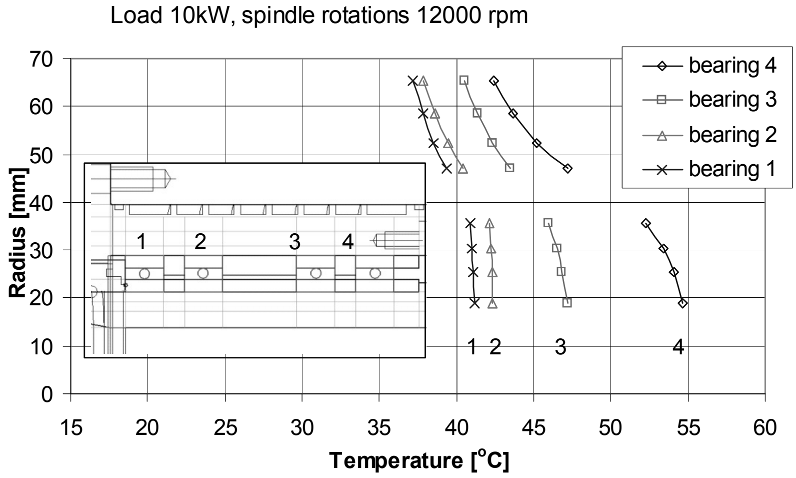


Fig. 8. Temperature distribution in cross sections determined by front electrospindle support bearings

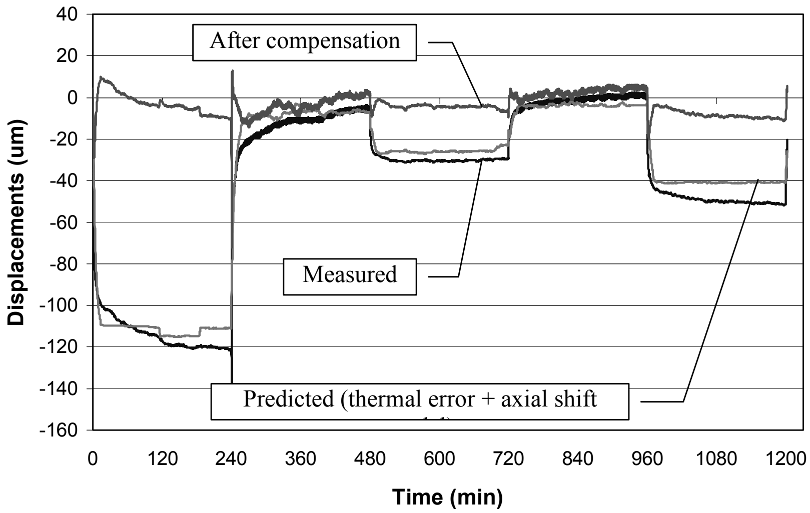


Fig. 9. Accuracy of predicting machining errors during variable cycle of operation of vertical machining centre

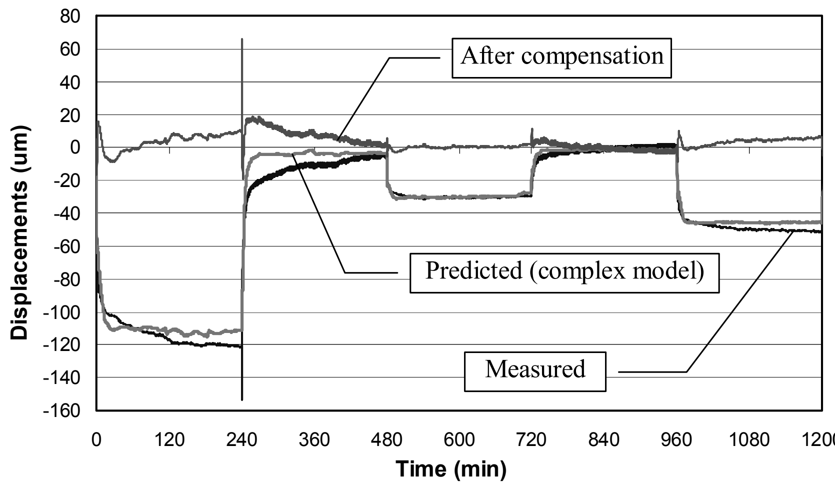


Fig. 10. Accuracy of predicting machining errors during variable cycle of operation of vertical machining centre by means of integrated model

In order to determine the correlations, the straightedge and the variants of its fixing were included in the model and error simulations were run depending on ambient temperature variation over time. The three cases (a, b, c) of straightedge fixing to the machining centre support beam are shown in Figure 11.

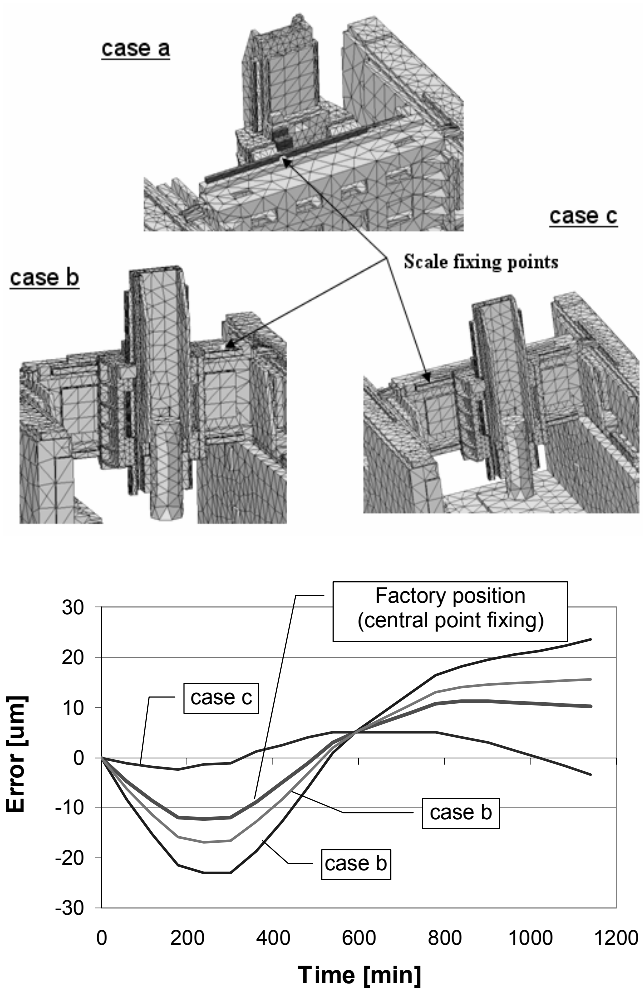


Fig. 11. Effect of straightedge fixing location on measuring error: case a) – central point fixing and glass scale moved to the right side; case b) – factory position and fixing point moved to the right side of glass scale; case c) – factory position and fixing point moved to the left side of glass scale

For the central position of the headstock on the beam the smallest errors occurred when the glass straightedge fixing point was moved left (c). One should note that according to the base design the straightedge was to be centrally located on the beam and fixed in the middle. Using the results of this analysis one can significantly reduce spindle position measuring errors arising from changes in ambient temperature.

7. Conclusions

From the above analyses and examples of modelling the thermal behaviour of machine tools one can conclude that only integrated modelling of all the phenomena which affect the displacements of machine tool components can be effective. It is very difficult to model, with an accuracy sufficient for practice, the transitional states accompanying sharp changes in spindle speed. This applies particularly to complex states of forces and deformations in the spindle assembly components, which change very dynamically at every change of spindle speed.

Modelling and analysis should cover not only the behaviour of the machine tool structure but also the path measuring systems. By analyzing the behaviour of the straightedge one can optimize its position and reduce measuring errors arising from ambient temperature variation.

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