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PRECISE MODELLING OF MACHINE TOOL DRIVES WITH BALL SCREW THERMAL BEHAVIOUR

This paper briefly describes the current requirements which machine tool ball screws must meet and indicates the need for the modelling and numerical simulation of the latter. The structure of a holistic ball screw model and ways of modelling the properties of the ball screw in a turning centre, including the moving heat sources on the guides and in the screw-nut joint, are presented. The results of computing the heating up and displacements of a preloaded screw and the screw without preload are reported. The modelled changes in motion resistance and in displacements are shown to be in agreement with the results of measuring the current drawn by the drive's motor. It is also shown that the models represent well the real physical phenomena occurring in the ball screw during the execution of repeatable work cycles by the drive.

1. INTRODUCTION

Ball screws – still the main component of the machine tool controllable axis linear feed drive – have a decisive influence on the efficiency of this drive and on positioning accuracy. They are expected to ensure high feed dynamics for high speed cutting (HSC) while the required speed is quickly reached through high accelerations and jerks. Also high positioning accuracy, dictated by the high dimensional machining accuracy requirements, is expected. Positioning accuracy is disturbed mainly by the thermal deformations of the ball screw and of the assembly within which it operates, and also by the deformations of the other machine tool assemblies, such as slidable tables/slides, beds, columns, etc.

Since the thermal deformations are affected by many structural factors and operational factors, such as dynamics, friction, loads generated by slidable masses, ambient temperature variation and interactions, their character is very complex.

In order to increase positioning accuracy the phenomena having a bearing on this accuracy need to be accurately identified through the holistic modelling and numerical simulation of the thermal behaviour of the ball screw and the behaviour of positioning errors

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in the natural machine tool operating conditions. In order to satisfy the latter condition it is necessary to model moving heat sources. Otherwise, it is not possible to accurately identify the deformations which vary during the machine tool duty cycle.

In the most advanced research aimed at identifying the factors affecting the thermal errors of machine tool ball screw drives one can distinguish:

- experimental studies of power losses and heating up, including temperature variation along the screw and positioning errors, aimed at identifying the phenomena accompanying the operation of drives with a ball screw [1],[2],[3];
- research on modelling the physical processes causing thermal deformations of the ball screw [4], assuming the trapezoidal distribution of the heat flux transmitted from the nut to the screw and based on the recognition of screw temperature by a thermal imaging camera [5] and on measurements of the power consumed by the drive motor [6];
- research on a moving heat source model, coming down in [7] to the stepwise shifting of the slide, whereby it became necessary to renumber the nodes of the discretization mesh. This made it impossible to model the dynamically changing resistances to motion in the nut and in the guides, occurring during the execution of fast (lasting fractions of a second) slide approaches and retreats. Similar attempts at pseudo movement had been undertaken earlier [8] by the authors of this paper.

2. INVESTIGATED OBJECTS

This paper presents the results of the simulation of the thermal behaviour of the ball screws in the drives of the turning centre slides in axes X and Z (Fig. 1) for naturally modelled heat sources occurring in the moving nuts, the screw bearings and the motor as well as on the guides. Also the loads resulting from friction and from the inclination of the controllable feed axes, due to gravitation and to the inertial forces arising during acceleration and deceleration, were taken into account.

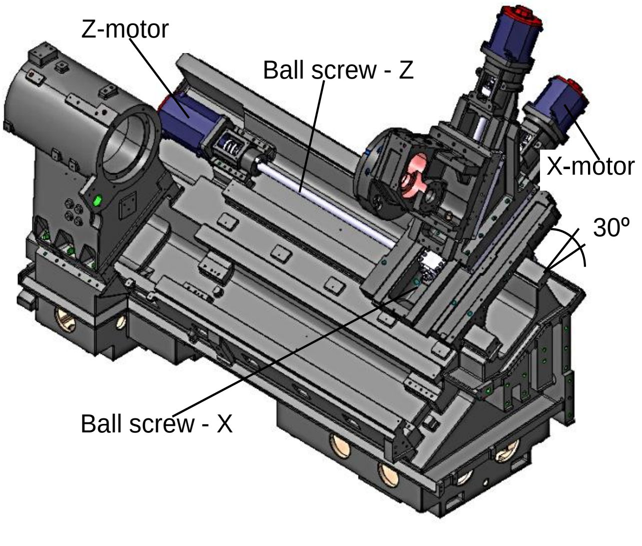


Fig. 1. Turning centre feed drives X and Z

Since it is shaped by all the thermal and force effects and the interactions between them, positioning accuracy very well characterizes the feed drive design. Therefore the thermal elongations of the drive components and the deflections of the latter caused by the pulling force and the friction forces, as well as the dependences between the power losses, the stiffness of the bearing supports, the stiffness of the nut-screw joint and the stiffness of the screw itself are taken into account.

The analysis of ball screw incorporating drives covered several aspects having a bearing on the intensity and variability of the heat sources (the motor, the bearings, the nut-screw joint and the guides) and on the displacements caused by external forces and friction forces. The aspects are: nut preload, nut/screw friction, slideway friction, bearing friction, screw preload, inertia, gravity, stiffness, axis inclination and environment.

3. MODELLING BALL SCREW BEHAVIOUR

A general holistic model of ball screw behaviour in the machine tool, including the interactions, is shown in Fig. 2. The model incorporates two component models, i.e. a model of the loads acting on the moving assemblies and a model of the power losses (heat sources) and of the displacements causing thermal interactions and positioning errors. The indicated force, thermal and displacement interactions between the ball screw mechanical components (P, T, D and L) show the complexity of modelling the thermal behaviour of the ball screw. Since the reactions to the loads produced by the frictional and inertial forces of the moving masses of the driven assemblies change with the rate of feed, this rate has a significant effect on the power losses and thermal errors in the controllable axes.

The first object of modelling and simulations was the longitudinal feed drive of the slide in the turning centre Z-axis. The slide moves on sloping guides situated at different heights (Fig. 1). The slide weight component in the direction tangent to the guides, was carried by only the lower guide and the distribution of the masses on the slide was not symmetrical to the guides. This resulted in different frictional resistances on each of the guides, generating a reactive force on the screw. Also the inertial force acting on the shifted slide added to the frictional resistances on the guides and the screw motion resistances. A friction coefficient changing with the rate of feed was included in the model of friction in the slide/guides assembly. Because of the horizontal position of the guides a change in the direction of movement in the Z-axis results in only a change in the direction of screw reaction.

Then the behaviour of the ball screw in the X-axis of the lateral feed of the slide base with its guides inclined at an angle of 30° to the horizontal (Fig. 1) was modelled and analysed. In this case, the resistances to upward and downward motion are different, mainly due to the invariable direction of the gravitational force. Consequently, the X-axis drive and the Z-axis drive differ in the forces acting on the screw-nut assembly and on the screw bearings, not only because of the different masses being moved, but also due to the different reaction to changes in the direction of motion. The interlinkage of the two drives in the machine tool structure is shown in Fig. 3. The X-axis drive assembly is secured to the Z-axis longitudinal slide base. In addition, the axial thermal elongations of the screw in the Z-axis drive proceed away from the drive motor, whereas in the X-axis drive they proceed towards the motor. This is due to the position of the screw supports incorporating respectively a set of preloaded angular bearings (the FIX support) and a set of floating angular bearings (the FREE support). The thermal displacements of points on the screw will be always directed towards the FREE support.

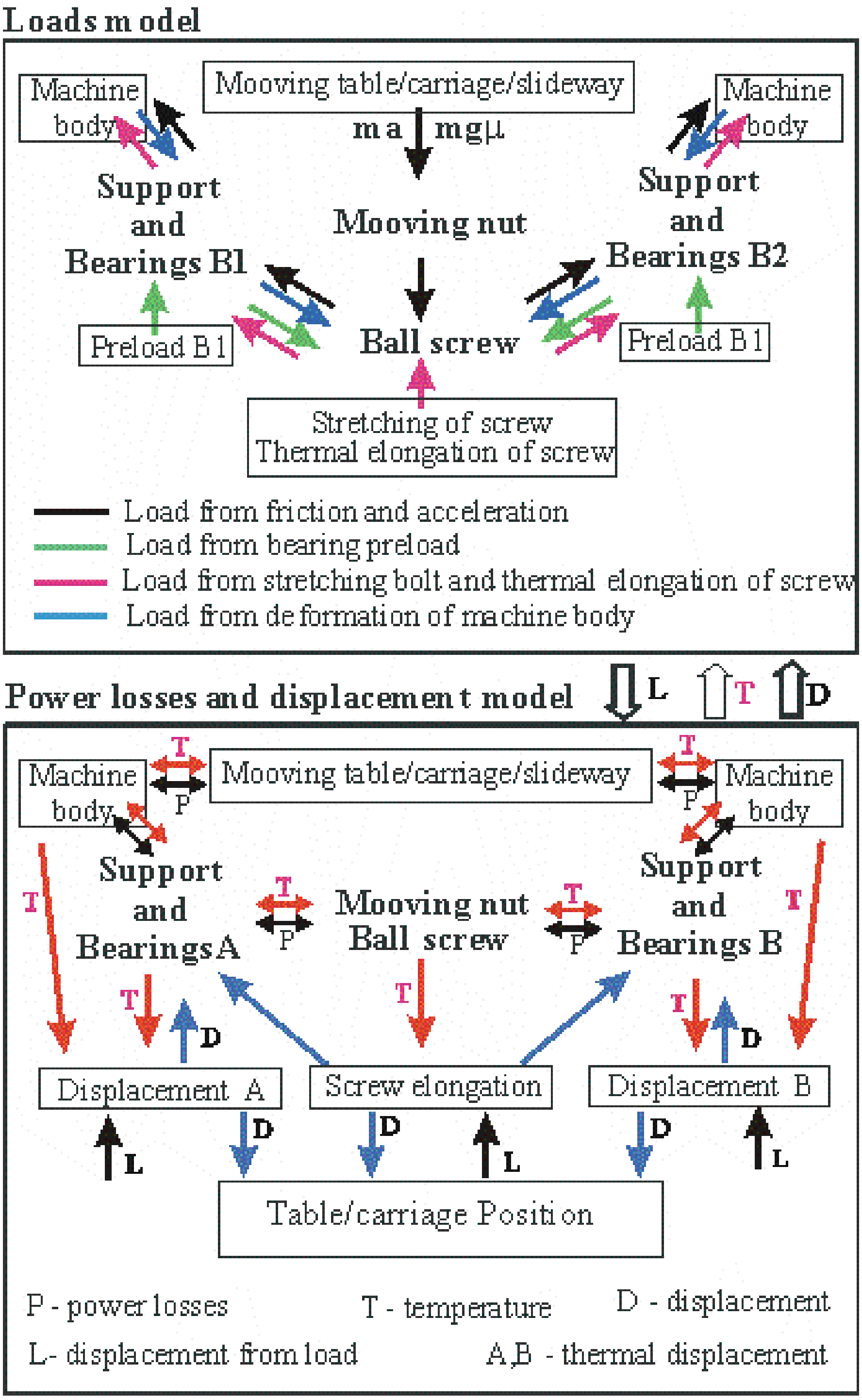


Fig. 2. Holistic model of drive with ball screw in machine tool structure

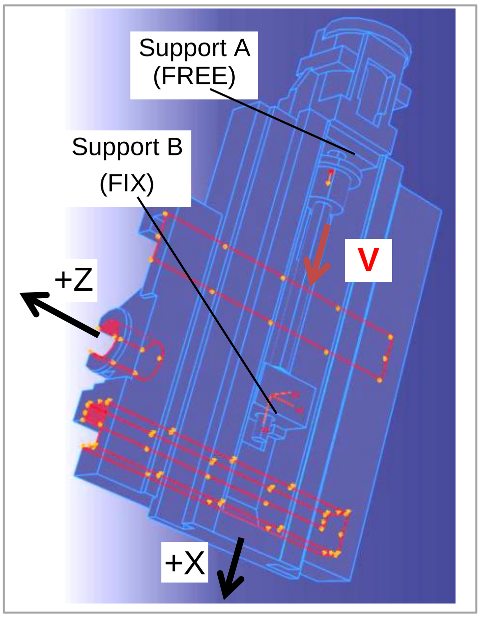


Fig. 3. Interlinkage of drives Z and X in turning centre through machine tool bed slideways

In precision feed drives incorporating a ball screw the screw is usually preloaded by stretching. The aim is the self-compensation of its thermal elongations in operating conditions. This has a direct influence on positioning accuracy. The screw in the modelled Z-axis drive was preloaded by stretching it by 50 μm, which resulted in the increased loading of the bearings in the screw's both supports and in the elastic deflections of the latter. As the temperature rises as a result of heating up, the preload of the screw must decrease commensurately with the degree of heating, down to zero. Also the preload of the supports must similarly diminish. In order to model the prestretching of the screw by 50 μm (measured at the screw end) not only the stiffness of the screw, but also the compliance of the bearings in supports A and B and the compliance of the supports themselves had to be taken into account. Consequently, the actual elongation of the screw in the unheated condition, to be entered into the Z-axis drive model, was considerably smaller (amounting to about 42 μm).

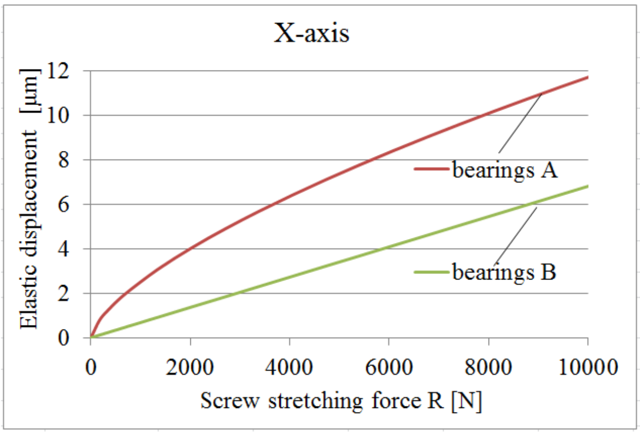


Fig. 4. Elastic displacement of support bearings

In order to properly represent the self-compensation of the thermal elongation of the screw as the latter heats up it was necessary to enter the stiffness characteristics of the bearings as a function of the screw stretching force into the model (Figs 4 and 5).

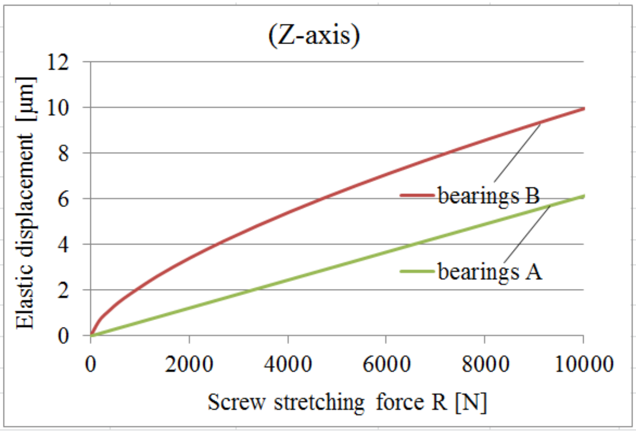


Fig. 5. Elastic displacement of support bearings

The preloaded bearings in the FIX supports (bearings B for the X-axis and bearings A for the Z-axis) have a linear stiffness characteristic. The floating bearings loaded with solely the screw stretching force (the FREE supports) have a nonlinear characteristic. Also changes in the screw stretching force which loads the bearings contribute to changes in the power losses in the latter. The diagram drawn for the bearings in the Z-axis drive (Fig. 6) shows how important it is to take into account this phenomenon.

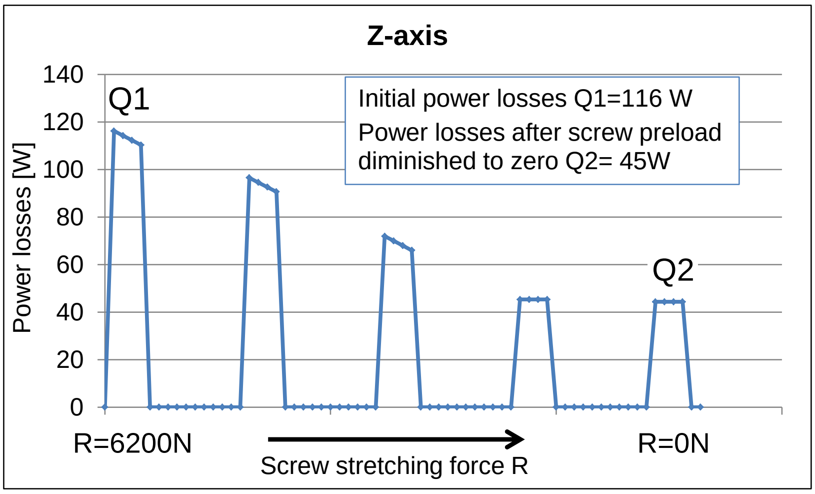


Fig. 6. Changes in power losses in support B bearings as Z-axis screw pre-load diminishes

In order to model the heat sources, except for the friction on the guides, it was necessary to determine their intensity in each moment of the assumed drive work cycle. This applied to the power losses in the screw/nut assembly, the bearings and in the motor (Fig. 7).

For this purpose the relations reported in the literature and the manufacturer recommendations for calculating power losses during the acceleration, steady running and braking of the drive in accordance with the assumed work cycle were used [9],[10],[11],[12]. The linear characteristics of power loss variation for each of the three stages of drive operation were modelled as a function of time, as shown in Figs 8 and 9.

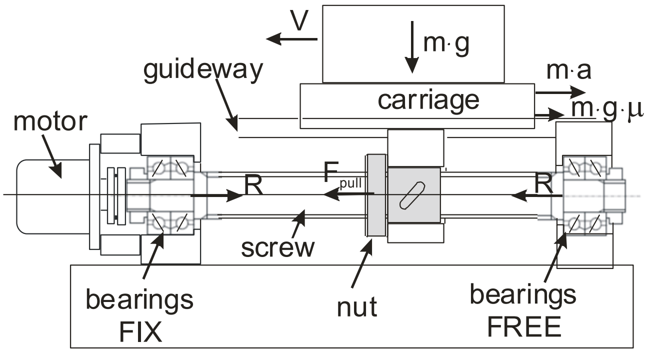


Fig. 7. Drive components of ball screw feed axes

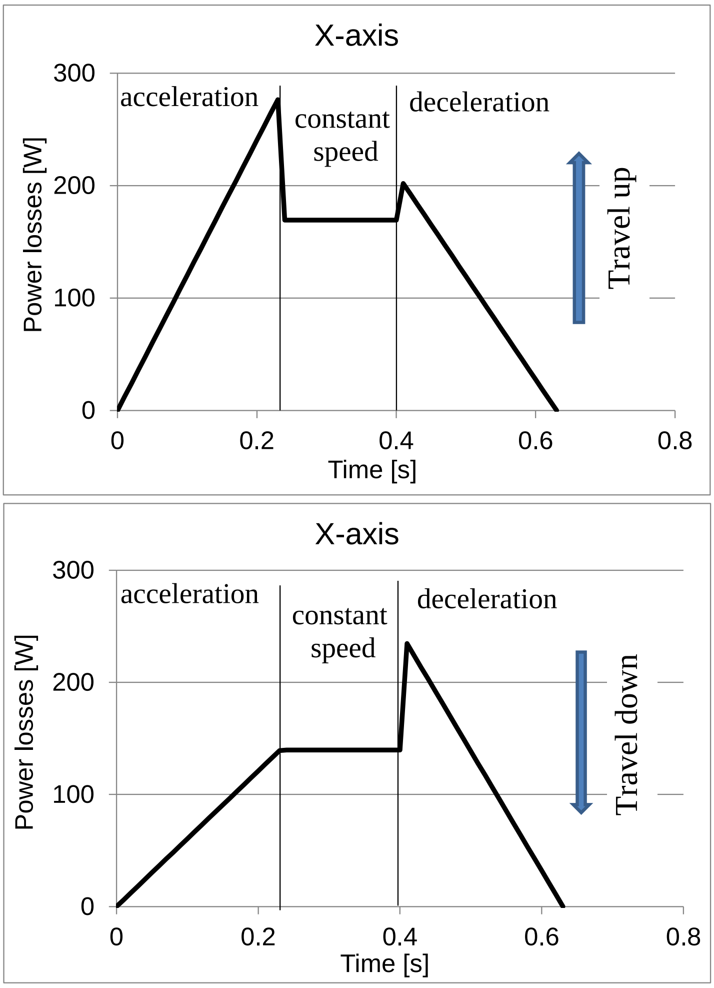


Fig. 8. Nut/screw power loses in X axis

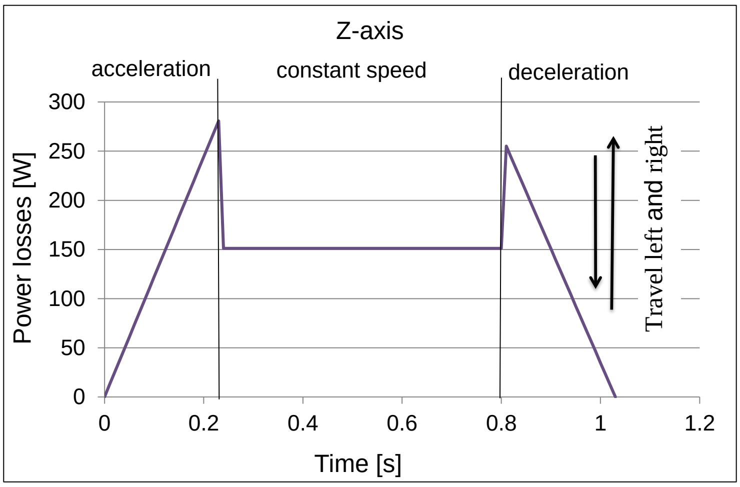


Fig. 9. Nut/screw power loses in Z axis

On the basis of real machine tool measurements the following were assumed for the Z-axis drive working at the maximum feed rate of 0.5 m/sec: acceleration time – 0.23 sec, steady running time – 0.57 sec and braking time – 0.23.

For the X-axis the quantities amounted to respectively: 0.23 sec, 0.17 sec and 0.23 sec. The power losses generated in the screw/nut assembly, calculated for the X-axis drive, to a large extent depend on the direction of motion, actually on the gravitational force and the inertial force, which during the motion upwards and downwards relieve or extra load the nut. In the FE model the losses were applied to the surface of the nut's grooves, uniformly along its entire length.

Most of the heat generated in the motor is transmitted to the ambient air and only a small fraction of it penetrates via convection, radiation and conduction to the screw and the bearing support. In order to calculate the power losses in the motor (Fig. 10) it was necessary to forecast the total motor shaft torque resulting from the motion resistances of the whole drive, i.e. the friction forces and the inertial forces.

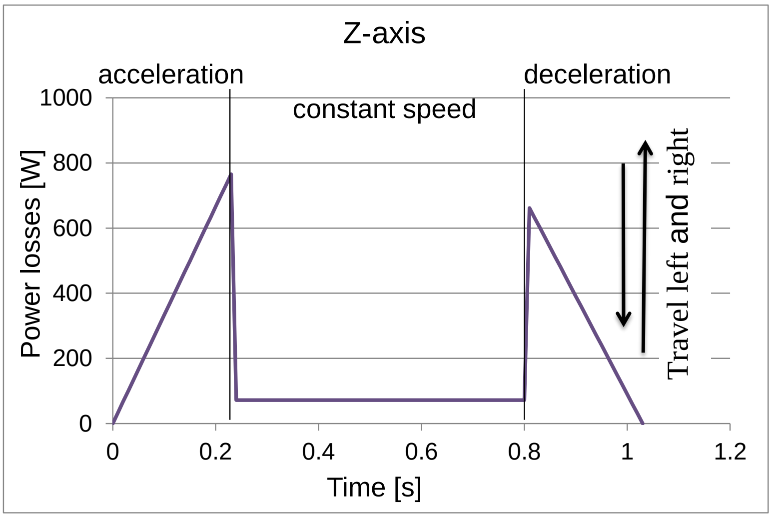


Fig. 10. Motor power losses for Z-axis drive

4. COMPUTATIONAL RESULTS

The starting point for evaluating the validity of the ball screw behaviour modelling and simulation were the results of measurements of the turning centre operating parameters, especially the current drawn by the motor. This current reflects the motor shaft torque resulting from the total resistance to motion in the drive, including the motor's own resistance to motion.

Figures 11 and 12 compare the measured variation in current (the motor loading torque) with the FEM simulated variation in resistance to motion (the pulling force) and in axial screw displacement.

The following repeatable duty cycles at the drives' maximum feed rate of 0.5 m/sec were assumed:

for the Z-axis

Pause 2(sec) ▸ Feed (distance -400mm) ▸Pause 2(sec) ▸Feed (distance +400mm),

for the X-axis

Pause 2(sec) ▸Feed (distance -200mm) ▸ Pause 2(sec) ▸Feed (distance +200mm).

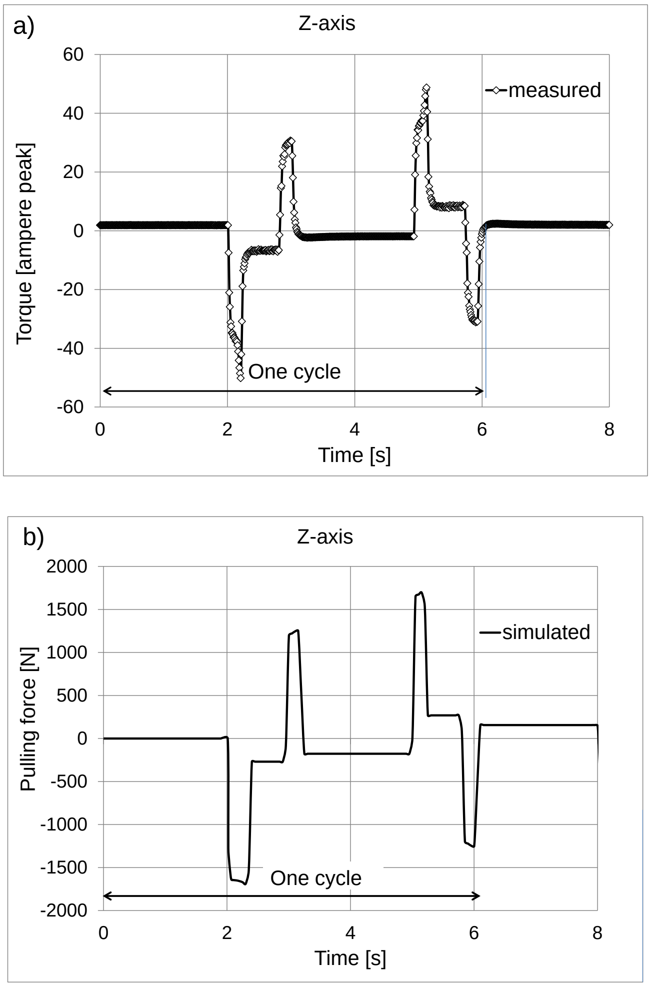
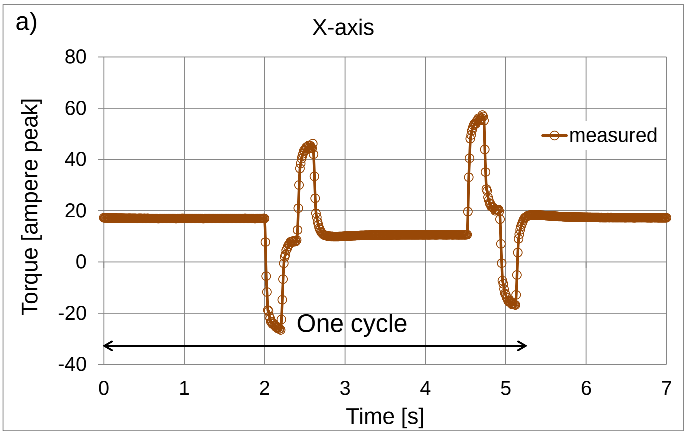


Fig. 11. Torque measured for Z drive motor (a) and numerically simulated pulling force in drive Z (b)



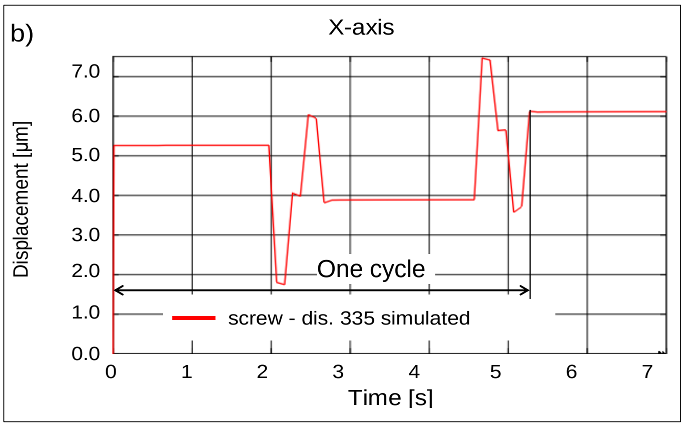


Fig. 12. Torque measured for X drive motor (a) and numerically simulated X screw displacement (b)

The FE models reflect well the dynamics of the change in the torques, as evidenced by the plots of the dynamic variation in total resistance to motion and in screw axial displacement, which are consistent with the pattern of the torque loading the Z-axis drive motor and the X-axis drive motor.

The repetition of the assumed duty cycle over longer time leads to the gradual heating up of the drive – the more intensive, the shorter the pause in the drive duty cycle. Figure 13 illustrates the heating up of the X-axis drive guides for pause = 2 sec.

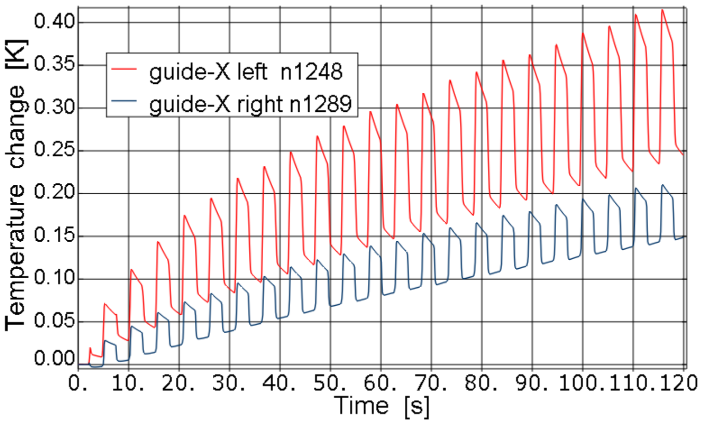


Fig. 13. Characteristic of guides-X temperature for operation time of 0-120 s

When the assumed duty cycle is repeated over longer time, the thermal elongations of the screw and of the other drive assembly components must lead to screw pre-load disappearance. Numerical simulations showed that this effect occurs in the Z drive after about 900 minutes of operation (Fig. 14). After this time the displacements of the screw increase more rapidly (Fig. 14b) – as they would increase for the unstretched screw.

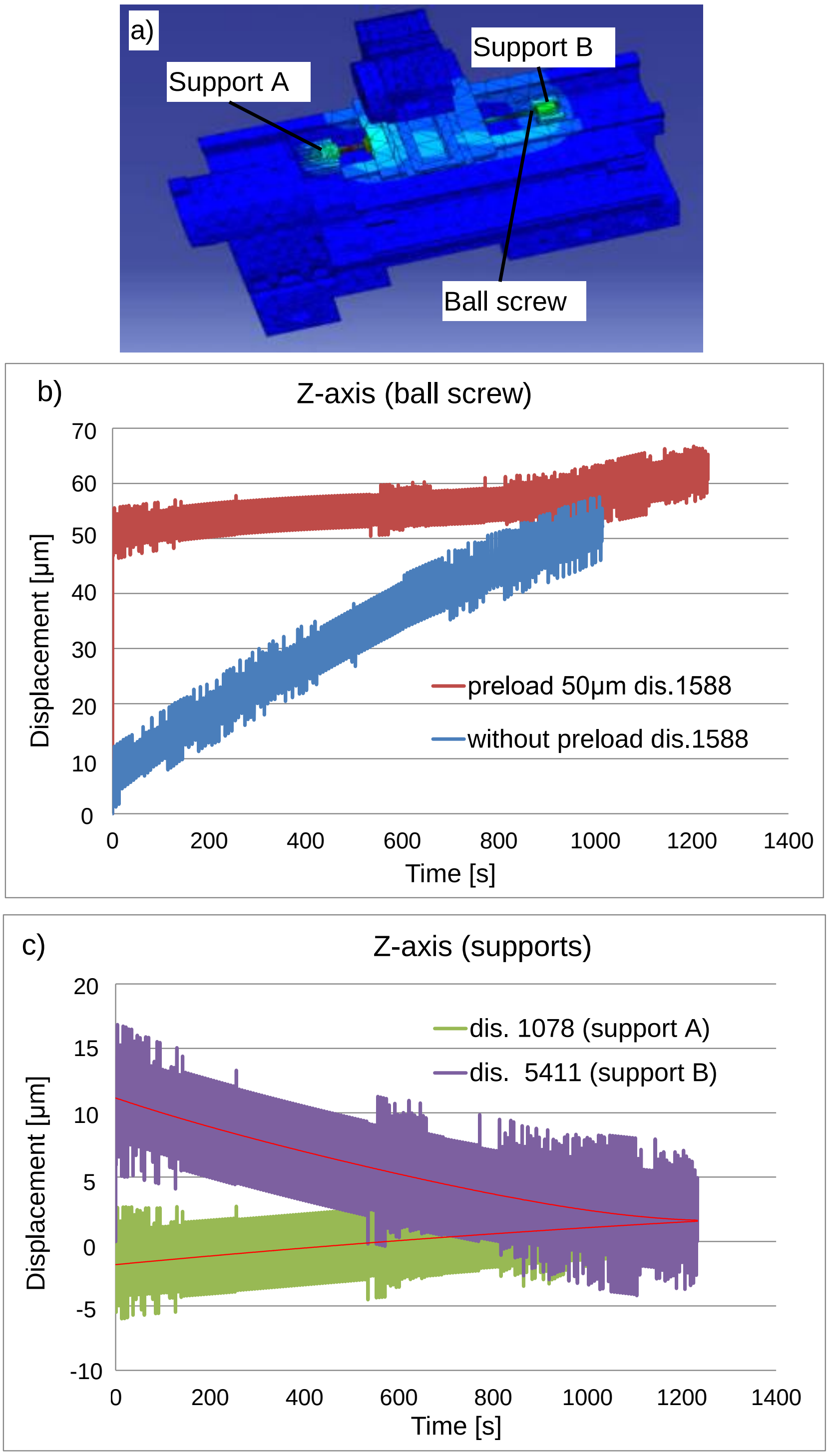


Fig. 14. Displacements of screw and bearing housings in Z-axis drive

The advantageous effect of screw preload is apparent in screw displacements, which are much smaller for the preloaded screw than for the screw without preload. The confirmation of the total unloading of the screw is the total decline in the displacements of the screw bearing supports, which become equal close to zero (Fig. 14c).

The straightening up of the supports which occurs as the screw heats up. especially of the support with preloaded bearings (support A for the Z-axis drive), significantly affects the direction in which screw points displace. In the case of the screw without preload, all the points situated along the screw displace in one direction, i.e. towards the free support. Then a neutral point exists, which does not displace despite the fact the screw heats up, and the points situated on its two side displace in opposite directions. This is shown in Fig. 15, using as an example point 1523 connected with support A, which as the preload in the screw decreases, displaces to the left, pulling the screw behind it, while point 4189, lying on the screw in a clearly heated up area, already displaces to the right due to the considerable thermal elongation of the screw. In the considered case the neutral point (insensitive to the heating up of the screw) was situated between nodes 4162 and 4171. This point begins displacing towards free support B only after the screw preload vanishes.

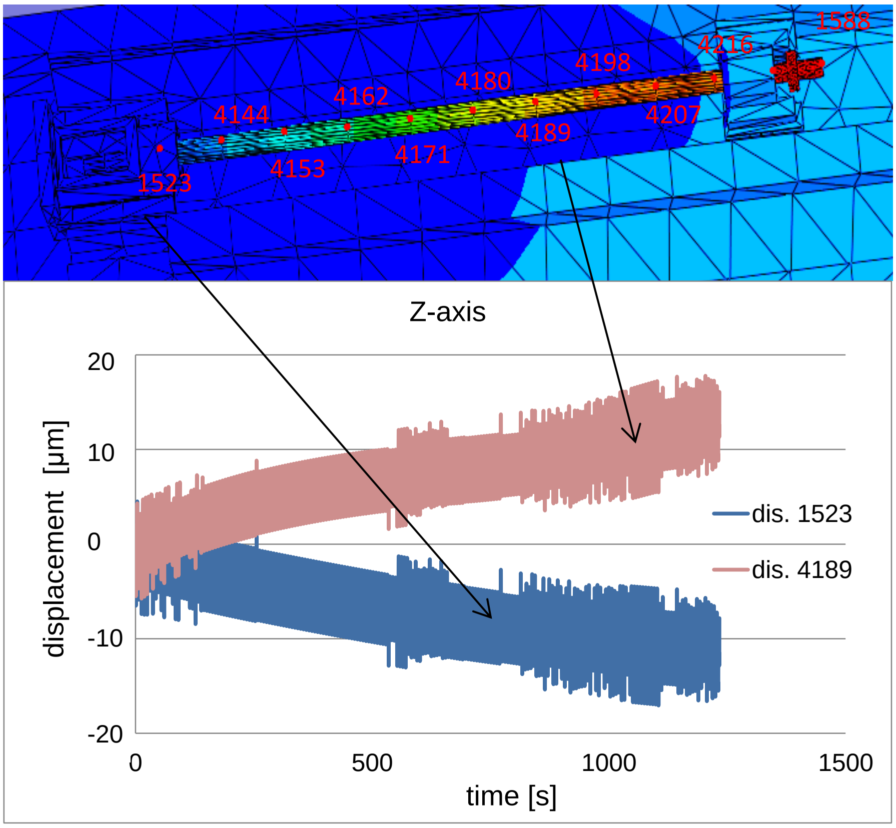


Fig. 15. Displacement of selected machine tool points during operation of drive in axis Z

In the above diagrams the computed temperatures and displacements are presented together with the variable component being the result of the dynamic drive operating conditions. The acceleration of the masses and the changing resistances to motion are reflected in temperatures and displacements in all the points of the modelled machine tool. In the case of displacements, the intensity with which these excitations will transfer to other drive components depends mainly on the latter's compliance/stiffness. When evaluating drive positioning accuracy one should use relative screw displacements, preferably relative to the stationary machine tool bed. In the example presented in Fig. 16 the displacements of the screw end (node 1588) in the Z-axis drive are related to node 1523 situated on the bearing housing (support A) connected with the machine tool bed. The variable component of the positioning error, which could be compensated using a CNC system, is several times smaller than the absolute displacement component. In this case, it does not exceed ±1μm.

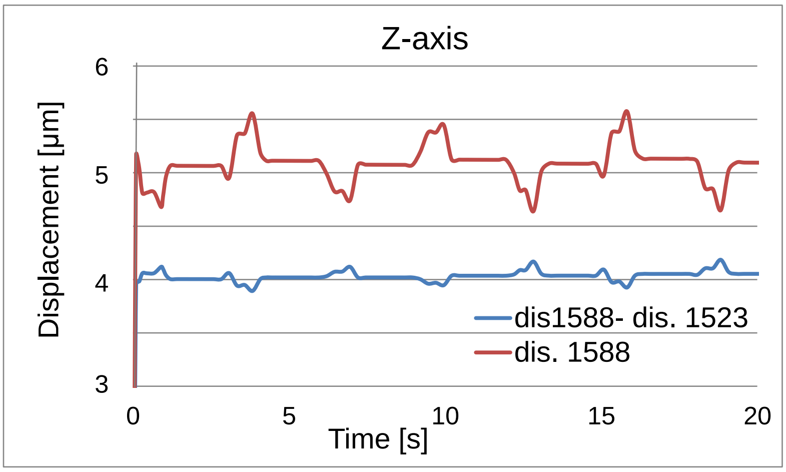


Fig. 16. Variable component of screw end displacement (red line) and variable component of relative screw and displacement (blue line)

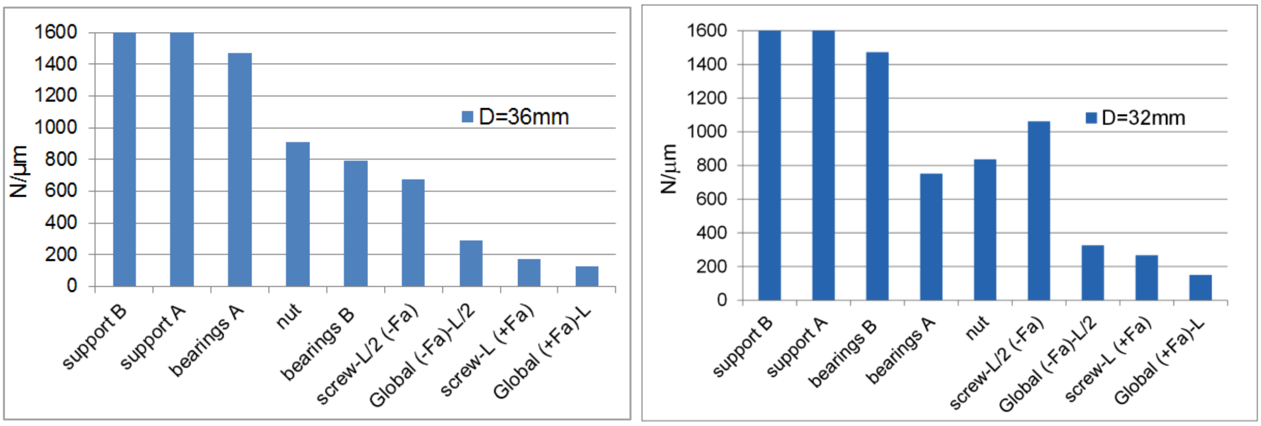


Fig. 17. Stiffness of axis drive: a) Z-axis, b) X-axis

Also the results of the analyses of the static stiffness of the drive components in the axial direction under the action of external force Fa (the cutting force) can be of interest to designers. The determined stiffness values are presented in Fig 17, where:

L/2 – the nut in the middle of the screw length,

(-Fa) – force Fa directed towards support A.

The weakest links in the Z-axis drive are the ball screw and the bearings in support B. This determines the global stiffness of the drive, which is close to 300 N/μm, but only when the external force acts towards support A and the nut is in the middle of the screw length. The situation is somewhat different in the X-axis drive where the weakest links are the bearings in support A and the nut.

5. CONCLUSIONS

1. It has been shown that the loads, temperature distributions and displacements which occur in the ball screw in the natural conditions of executing slide feed at a rate of 0.5 m/sec can be very precisely numerically simulated.
2. It has been shown that the moving heat sources characterized by variable output, occurring on the guides and the nut during the movement of the slides along the Z and X axes, having a significant bearing on the distribution of temperature along the screw, the axial displacements of screw points and positioning errors, can be modelled.
3. The model accurately represented the variation in screw load during the execution of the assumed drive duty cycles, including the transition states connected with acceleration and deceleration. Despite the high dynamics of changes, due to the short acceleration/deceleration of 0.23 sec, good agreement between the variable displacement component and the measurements of the current drawn by the motor was obtained.
4. It has been shown that screw preload has a strong effect on the positioning error value.
5. The unpreloaded screw bearings and the nuts have been shown to be stiffness-wise the weakest components of the drive with a ball screw.

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