OPERATIONAL BEHAVIOUR OF HIGH SPEED SPINDLE UNIT

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The paper presents the behaviour of a high speed spindle unit during operation, with changes of: speed, centrifugal forces, bearing working clearance/tension, thermal deformations and temperature distribution. Moreover, spindle and rolling elements of bearing material's influence on heating up and spindle displacements will be shown for different spindle working conditions.

Keywords
machine tool, spindle unit, high speed

1. Introduction

Contemporary efficient manufacturing requires machine tools for precise and high-speed cutting (HSC). High cutting speed is ensured by motorspindles with roller bearings. Their construction should ensure not only the achievement of high and very high rotational speeds of spindles, but also the highest possible dimensional and shape precision of machined parts. Therefore they must distinguish itself by a high rotational movement precision, high stiffness and a small thermal displacement of a spindle in cutting conditions. Machine tool manufacturers need spindle unit constructions as close to perfection as possible, which besides above mentioned characteristics must also be characterized by a very high durability.

Motorspindle manufacturers try to provide them with the most recent constructional solutions of bearings, well suited for high and very high rotational speeds – ensuring correct working conditions of rolling elements, required tension in the entire range of rotational speeds as well as a high durability. In order to make rational decisions in choosing the constructions of spindle assemblies it is important to know their behaviour in working conditions. The main intention of the authors is the explanation of phenomena appearing under the influence of some constructional and operational parameters in spindle assemblies, influencing their suitability for HSC.

2. Requirements for spindle assemblies

High-speed spindle assemblies have a constantly increasing use in cutting machine tools, especially in machining centers. High rotational speed of a spindle is indispensable for conducting the precise machining – for precisely cutting the shape, dimensions and roughness of a part. The increase of a rotational frequency of a spindle with ball bearings causes the load characteristics of rolling elements, bearing raceways and all rotational elements to change, resulting from centrifugal forces, increasing with speed [Altintas 2005], [Chen 2006]. The effect of such forces are deformations directly influencing the load conditions of a bearing and the distribution of internal forces, as well as the location change of spinning elements. Also the contact angles of bearings change, modifying the kinematic transmission ratio in a bearing (see Figure 1).

From the construction and exploitation point of view the spindle unit must have a required stiffness, as well as the lowest possible axial displacement time runs – repeatable and easy to compensate. Therefore, the phenomena taking place in a spindle unit must be precisely identified. In order to limit the disruptions of spindle unit's operation, such disruptions must be precisely modelled, which also allows for the precise real-time error compensation [Jedrzejewski 2004], [Jedrzejewski 2007]. The more complex are the spindle assemblies, the more complex are the displacements of the entire unit and the summation of displacements caused by forces and thermal displacements.

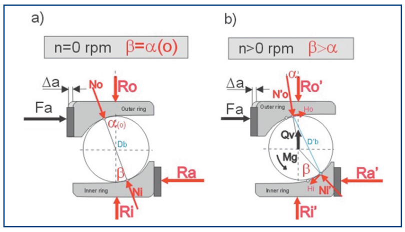

Figure 1. *Balance of internal, external and reaction forces acting on a rolling element and bearing rings.*

The goal of this paper is to show the behaviour of a high-speed spindle unit, in which the preload is accomplished by means of a spring and a moving sleeve. In order to present the phenomena taking place in a high-speed spindle unit, two headstocks have been used, with maximum rotational speeds of 50 000 rpm and 20 000 rpm [Jedrzejewski 2008].

3. Axial displacement of a spindle

Deformations and displacements present in the spindle/motorspindle itself have a dominant influence on axial displacements of a spindle, during the change of a rotational speed and during constant operation. The larger sudden change of rotational frequency, the larger are the sudden changes of the spindle tip's location. It is clearly seen on the example of an assumed rotational speed change cycle in the speed range of 0 – 20 000 rpm (see Figure 2). The changes of a rotational speed, according to the schematics shown on the upper side of the figure, caused axial displacements of a spindle, shown on a graph with a thick black line.

In a moment of the speed change, a sudden change of axial displacements takes place followed by a time-constant displacement reflecting a thermal elongation/contraction of a spindle, which dominates in the period of operation with a constant rotational speed. This adds up to the thermal displacement/ deformation of a headstock body and the body of the entire machine tool caused by inner

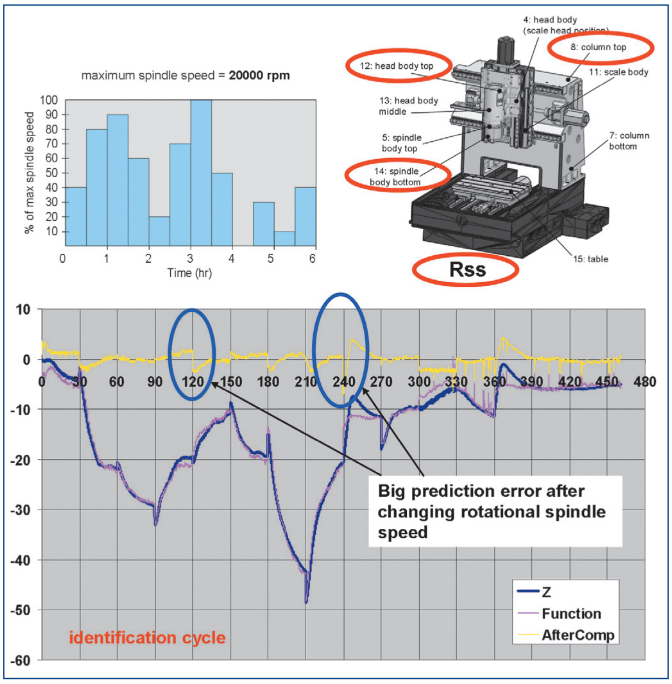

Figure 2. *Experimentally identified and predicted machining centre spindle displacement and theoretical compensation accuracy.*

heat sources and the influence of the ambient temperature. Red line on this graph reflects the representation of such displacements by means of a regression function.

The differences between displacement values shown by both lines are presented by the yellow line. These differences reflect the precision with which transient states and constant speed periods are represented by a regression curve. The largest problems which still need solution exist when representing transient states, especially hard to identify irregularities visible on the curves obtained from measurements. The result of such problems are the appearance of areas, marked on a picture, of relatively low precision of a spindle displacement compensation. In order to analyze the behaviour of a specific spindle unit, an motorspindle shown on Figure 3 has been used. Preloading of bearings is accomplished by means of a moving sleeve tightened by a spring with a force of Fspr.

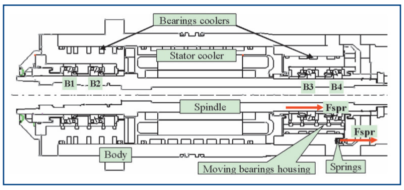

Figure 3. *High-speed headstock with spring tensioning spindle bearing.*

The behaviour of a spindle measured during the idle operation with defined rotational speeds and during the changes of such, has been shown on Figure 4.

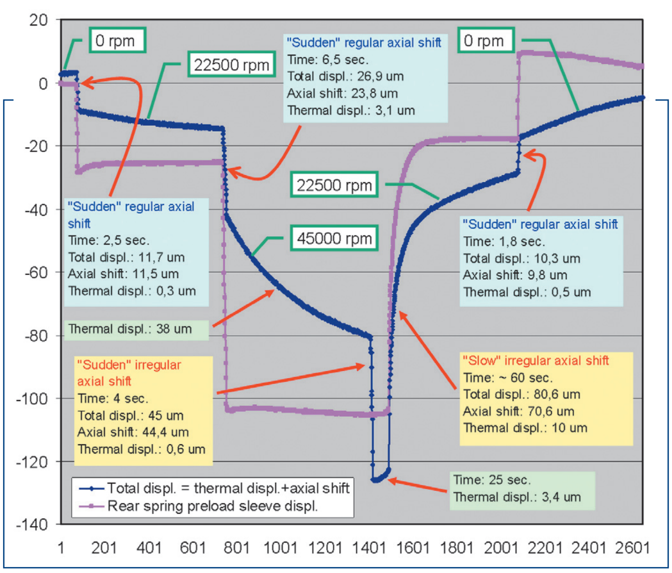

Figure 4. *HS machining centre spindle shift with overlapping thermal elongation, and sleeve movement analysis.*

The figure clearly shows that enabling the 22 500 rpm speed is accompanied by an axial shift of a spindle, marked by a black line, followed by the constant rise of a displacement, being an effect of spindle's thermal elongation. Further sudden speed change to 45 000 rpm is characterized by an even larger shift, followed by an intensive thermal elongation. During the change of speed from 45 000 rpm to 22 500 rpm a large extension of the spindle is noticed, which is an effect of a sudden change in bearing contact angles to the values appearing at the speed of 22 500 rpm. At a low rotational speed bearings are very axially stiff, therefore in order to accomplish the assumed preload, a smaller displacement of outer rings is needed than in case of higher speeds. The value of a spindle shift is observed after the decrease of a rotational speed corresponds to the difference in displacements of outer rings, needed for achieving the preload defined by the spring force.

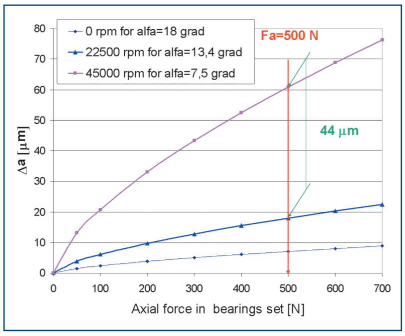

Figure 5. *Axial stiffness of a set of two angular bearings with pitch diameters of 61 mm, for two rotational speeds.*

Such phenomenon is explained by a Figure 5, picturing the relation of bearing rings axial approach to the axial force (spring force) preloading the bearings.

The approach Δa needed to exert the bearing pretension of 500 N for the rotational speed of 45 000 rpm is ca. 44 μm larger than for the rotational speed of 22 500 rpm. This corresponds to the value of a shift observed in measurements. Consequently during 25 s a thermal contraction of the spindle is observed, since the sleeve still has not acted (it is jammed). After the action of the sleeve a retraction of the spindle and a decrease in its thermal elongation takes place.

During the next rotational speed change to zero a shift is observed, of the value similar to the value appearing during the start. Next, an effect of spindle cooling is observed. It is also seen, that the spindle after finishing the cycle of rotational speed changes does not return to its original position, which is due to the thermal deformation of the headstock body and the entire machine tool. The behaviour of the sleeve preloading the bearings is shown by the violet line. This sleeve, as a result of deformations and tendencies of angular displacements, does not fulfill its basic function well, i.e. self-acting compensation of spindle's thermal elongations. However, such fault (jamming of a sleeve) allowed the appearance of spindle shifts taking place after the reduction of a rotational speed, which with a properly working sleeve should not be visible. This allowed for a simple verification of stiffness-based bearing models. If the sleeve had not been late with the reaction to the decrease of inner loads in bearings, the expected immediate return move of a sleeve would have disallowed the observance of phenomena related to the change of bearing stiffness.

Naturally such fault should be prevented, preferably by the replacement of a sliding sleeve by one mounted on rolling elements with a suitable preload [Jedrzejewski 1988]. In order for the prediction and compensation of a spindle displacement to be possible in any working conditions, one must have a precise model of the spindle unit behaviour.

4. Modelling of spindle's axial displacement

The basis for modelling of spindle's axial displacements is a bearing model described by balance equations of forces and moments acting on a bearing during operation. In angular ball bearings, centrifugal forces acting on balls force the change of ball contact points with raceways. This results with the bearing contact angle α(o) different for a contact with the outer raceway and for the inner raceway. The consequence of such behaviour is not only the change of bearing axial stiffness, but also a completely new balance state of forces and moments is created in a bearing. Due to the difference of contact angles on both rings, all forces and reactions projected on axial direction do not balance. The value of such unbalance has been labelled on Figure 6a as Fx. Such phenomenon causes the increase of an axial force in the bearing preloaded with the force of Fa. If a preload is realized by means of springs (Figure 6b), then the force Fx causes the displacement of the outer ring by a value of Δa proportional to the stiffness of jsp springs. As it appears from the presented graphs, too low pretension is not only the cause of large sleeve movements, but it can also disallow the operation of a bearing with high rotational speeds. The construction of every bearing imposes a certain maximal value of the contact angle with the inner ring. If the balance of forces requires a larger angle than the value allowed by the construction of a bearing, its kinematic and frictional working conditions will be incorrect, and may result in the destruction of a bearing.

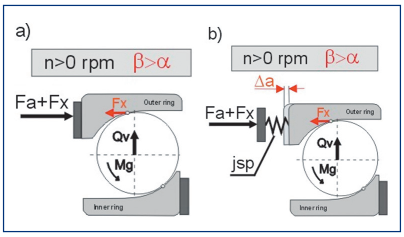

Figure 6. *Changes of pretension force of a bearing with pitch of 61 mm, in working conditions.*

Axial movements of a spindle in motorspindles are strictly connected with the movement of a sleeve preloading bearings, appearing during changes in a rotational speed. For the construction shown on Figure 7 they translate only in 50% to displacements of a spindle Dsp, according to the dependence shown on the same figure.

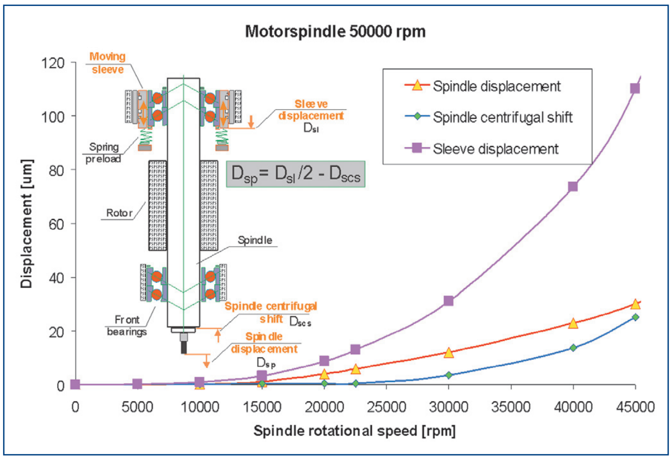

Figure 7. *Prediction of spindle's axial displacements.*

The second component the of spindle displacement, compensating sliding sleeve movements Dsl is the decrease of spindle length Dscs (spindle centrifugal shift) due to centrifugal forces acting on a spindle. Therefore, utilizing the model of inner loads in a bearing it is possible, based on the calculations of sleeve movements and spindle contractions in relation to a rotational speed, to forecast the behaviour of a spindle tip during changes of a rotational speed.

5. Influence of the material and the cooling of bearings

It is commonly known, that the decrease of the spindle unit's thermal load is achieved by decreasing the diameter and mass of rolling elements, ensuring the optimal thickness of oil film – elastohydrodynamic, decreasing the inner loads and the friction coefficient of contacting elements – balls and rings. Additionally, a thermal expansion coefficient of spindle bearing components is very important. Small thermal capacity of the spindle itself causes it to heat up and deform more than the housing, which additionally is in a natural way better cooled. Moreover, a forced cooling of the engine's stator is usually required and together with it, a cooling of a bearing set.

Figure 8 shows temperature changes of front T1 and rear T2 bearings of a spindle unit in a machining center, as well as accompanying thermal displacements of the spindle's Z axis. Constructional solutions using bearings with steel and ceramic balls have been analyzed, not expecting the use of a bearings' forced cooling, as well as solutions including their forced cooling. As a medium in cooling systems, oil and water have been considered.

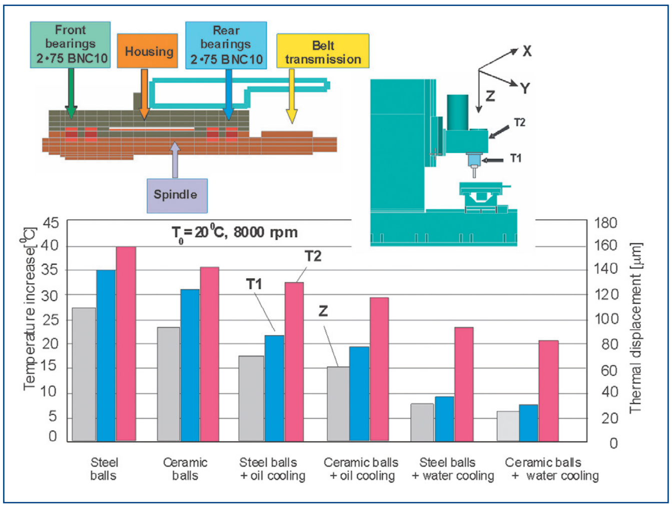

Figure 8. *Spindle unit thermal behaviour for different material of balls and cooling media.*

The results shown on a figure prove, that after substituting steel ball bearings with ceramic ball bearings, a 10 percent decrease of front bearings' temperature T1 and 15 percent decrease of spindle displacement Z should be expected. The use of headstock cooling by means of oil allows a 35 percent decrease of T1 and Z for solutions with steel ball bearings, while up to 45% with ceramic ball bearings. The highest improvements, up to 70% (steel ball bearings) and up to 80% (ceramic ball bearings), have been reached when using water cooling. Considerably worse effects of such actions have been noticed for temperatures of rear bearings T2. In the most favorable conditions, i.e. during intensive water cooling and ceramic ball bearings, their temperature still on the level of 50% of the value, which has been noted for a steel ball bearing without cooling. This is connected with the additional heat source near rear bearings, which is the belt transmission, located in a closed space. The results of calculations, which have allowed for carrying out of the hereby analysis have been fully conforming with the results of a practical application.

6. Influence of the spindle material

Spindle material, and especially its thermal expansion, has a great influence on the thermal behaviour of the entire spindle unit. Thermal change in a spindle diameter directly influences the tension of bearings, power losses and their durability. Hence the spindle should be made from a material with a low thermal expansion coefficient and, as far as possible, its heating should be prevented. Such prevention is generally based on decreasing power losses in bearings, forcing high thermal resistance of a contact between bearings and a spindle, which requires using special coatings [Winiarski 2006], as well as on using spindles with cooling from inside. Such inside cooling is hard to design and very costly. That is why it is more rational to compensate errors, as long as without cooling it is enough effective.

To present the influence of spindle material on the behaviour of high-speed spindle unit a parametric analysis has been performed, and its results have been shown on Figure 9. A behaviour of bearings no. 2 and 4 has been analysed, with preload of 300 N, loaded by (cutting) power of 18,5 kW, with rotational speed of 8 000 rpm. The bearings have been cooled – cooling canals are visible on the schematics.

From the figure it appears that the change of a spindle material from steel to ceramics has neither influenced the temperature of the

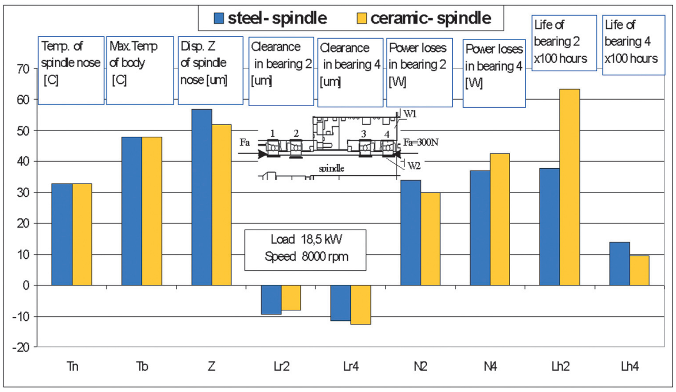

Figure 9. *Spindle unit behaviour by 8000 rpm comparison for steel spindle and ceramic spindle.*

spindle tip nor the headstock body, but it caused the decrease of the axial displacement of a spindle. Additionally, the change has slightly decreased the tension of the bearing 2, but also the tension of the bearing 4 has slightly increased. This results with an according decrease of power losses in the bearing 2 and an increase in the bearing 4. Such changes caused the lifetime of the bearing 2 to increase by 60 % and the lifetime of the bearing 4 to decrease by 25 %. Because of a much lower durability of the motorspindle's bearing set with the spindle made from a ceramic material, which is defined by the durability of the bearing 4; it is possible to derive, that the use of ceramic spindles is pointless.

7. Conclusions

In the bearings of high-speed spindle assemblies of machine tools, very complex states of internal tension take place. Centrifugal forces acting on spinning elements of bearings cause deformations of spinning elements, which have a great influence on values and directions of forces in bearings, as well as axial displacements of the spindle. These also have an influence on the power losses and durability of bearings. In the decrease of bearings' heating and axial displacements of a spindle, a large role is played by the material of rolling elements – substituting steel with ceramics. Whereas the substitution of spindle material: ceramics for steel; does not bring expected benefits.

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