Sensitivity study of spindle assembly used for thermal displacement reduction

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Abstract. The article is focused on the thermal behaviour of a spindle of a milling centre. This is a typical problem of high precision machines, which produce heat as a negative implication of production activity. Thermal loading influences productivity and precision of milling centre. Thermal transfer simulations, computed fluid dynamic solutions and finite element methods in general are vital sources of information about behaviour of machine parts influenced by heat loading. Reduction of thermal displacement is a crucial task. The sensitivity study, based on a complex case study, is able to identify features with significant influence on overall deformation. Complex case consists of detail subcase analysis. Identified parts require modifications to decrease of deformations. Results are compared with new productive computation method based on macro-models. Combination of these methods defines productive methodology which leads to fast prediction and accurate simulation.

1. Introduction

Machine tools are highly sophisticated mechatronic systems enabling manufacturing processes to a given high precision. The precision strongly depends on its thermo-elastic behaviour [1]. Internal and external structural properties also significantly influence the overall work accuracy [2, 3]. Based on Bergman, internal and external heat sources lead to a non-uniform and non-nominal temperature distribution resulting in elongation and mechanical deformations of the machine tool structure [4]. One of the main factors in mastering the thermal behaviour of machine tools is effective cooling, which is described by Mayr [1, 5]. This can be achieved by conduction through solid parts, by radiation, by free or enforced convection on outer surfaces or by forced convection with liquid cooling systems. Non-uniform distribution leads to areas with higher thermal loads, such as the main drive, the bearings or the cutting tool [6–9]. Direct cooling of cutting tools is used in almost all cutting processes. It provides cooling of the tool and lubricates the cutting area [10, 11]. In order to reduce thermally induced displacements, fluid based cooling systems are used. The main drives of machines can be cooled by air or by liquid circuits, while bearings are often cooled by liquid circuits and oil mist. Thus, controlling the thermo-elastic behaviour of machine tools to a large extent depends on the design of their fluidic system [11]. Fluidic system also provides data which may be used for thermal compensation [12]. In order to speed up the development and minimize the necessity for physical prototypes, it is essential to verify the design before manufacturing. Simulation of a complex system is a laborious task: it requires time to prepare computer aided design (CAD) models, skilled employees and computation time. That is
the reason why it is justified only for the verification of a final design. During the evaluation, it is helpful
to use an intermediate step with fast and simple computations. A method based on elementary elements
was developed for this purpose. The heat loading of the main part causes heat displacements, which are
significant factors in the precision of machining [13, 14]. Displacements of the spindles are also
examined in this article.

1.1 State of the art
Design optimizations, performance enhancing and precision requirement generate the research demand
in the field of thermal distribution, heat generation and thermo-mechanical behaviour [10, 15].
Thermal transfer simulations, flow simulations and structural calculations based on final element
methods are precise and sophisticated solutions for design optimization. These powerful tools provide
a vital data for the design. Required knowledge for CFD/FEM solution is considerable. A time
consumption and computation resources define high costs of the computation. Low value results in the
beginning of the design should be processed by less expensive solutions. These approaches are described
hereinafter [11].

1.2 Simulation – approach by combination of two principles
Described process was developed with implementation of new methods. Specific approach is
characterized by an implementation of macro-element computation method into the design process. The
present work deals with two statements: prediction and simulation. Accurate CFD or FEM simulation
in the beginning of the design is an expensive step with a low value of results. Improvement of the
process is based on predictive, macro-element calculation. This calculation promptly provides results of
thermal transfers and temperature fields. It is not a substitution of CFD simulation. It provides fast, basic
data in the beginning of the design process. Macro-elements are distinct models of specific design
features, described by elementary equations [7]. These equations are based on empiric and analytic
dependencies. Computation is significantly faster than simulation. The calculation is based on
elementary boundary conditions and provides raw data for design.

|                  | Prepare time | Computation time | Temperature computation | Result deviation | Costs |
|------------------|--------------|------------------|-------------------------|------------------|-------|
| CFD              | 1 hour       | > 600 s          | full                    | < 5 %            | High  |
| Macro-model      | 1/2 hour     | < 1 s            | partial                 | < 20 %           | Low   |

Table 1. Comparison of CFD/FEM simulation and macro-element calculation [16].

2. Analyses
Detailed analysis of a system of the machine is the beginning of the simulation. The section view in the
figure 1 shows the main features of a spindle of a large horizontal boring machine.

The main heat sources are shown: spindle bearing, transmission box - gears, electric components, etc.
The tool deformations are also identified: dilatation in y, z, w axes. Cooling effects are as following:

![Figure 1. Overall assembly analysis.](image-url)
cooling liquid circuit of final transmission, cooling liquid in centre of the spindle, convection cooling of environment, conduction in spindle body, radiation cooling of spindle body, etc. Thermal resistance of surface contacts is one of the important effects which influent the cooling of bearings. Every effect is analysed and described because of the inclusion to the overall, complex simulation.

2.1. Elementary cases
Details of thermo-mechanical systems are analysed. These details represent elementary cases, macro-elements. Dependencies in these elements are described by coefficients and empirical equations. Coefficients of heat transfer are discussed because of the high ratio of possible values. Boundary conditions of the heat transfer change their properties in a wide range of values. Coefficients must be evaluated. The method of searching of the coefficients is based on simple cases, simulated, measured and matched to the simulation data. NX Thermal/Flow solver is used for simulation of the effects. Calculations are based on a K-epsilon, K-omega or SST turbulent model. Essential properties in these calculations are wall roughness, advection schemes, etc. [16, 17]. Details of the elementary case evaluation were published [15]. A complex case is decomposed into basic features, an example being housing of the bearing, the bearing, and the cooling channel. These features are examined in isolated cases. The separated features represent basic macro-elements. Examples of these elements are presented below.

Numerical models used for the solution are based on Siemens NX software. Mesh bodies and calculations are defined in this complex platform. Solver of thermal/flow mechanism is based on implemented Maya technology. Structural behaviour is solved by Nastran solver.

2.1.1. Example 1 – Bearing definition
Spindle ball bearing is a vital part of the spindle assembly. The spindle bearings influent the overall precision and spindle function. Bearings are essential sources of heat. The ratio of generated heat in specific dimensions can be 50–800 W. Well explored component has non-trivial thermo-mechanical behaviour. Super-detail simulation with respect to rotation, ball movements, heat generation or stiffness is almost unprofitable. Inclusion of a few these complicated models into the simulation assembly maximize the computation time, with low value of results. Methodology of simulation and simplification of bearing features was stated due to that. The research has analysed three FEM methods, based on simplification. It is necessary to emphasise that simplification is applied to the thermal definition, not to the structural properties. The structural properties are defined by the properties of normalized bearings. Simplification of thermal/flow model:

- I. Heat load is simulated by the boundary condition of the heat load directly placed to the inner and outer rings. Boundary condition of the cooling properties cannot be reflected. The contact resistance between the bearing and the ram is neglected. The heat load must be decreased with respect to external calculation of the cooling capacity.

\[
\dot{Q} = \sum_{m=1}^{n} \dot{Q}_{\text{generation}} - \sum_{m=1}^{n} \dot{Q}_{\text{cooling}}
\]  

- II. The bearing is replaced by revolved geometry. Heat is generated in the ball groove. Surface area enables to define convection cooling and radiation effects. The area reflects the real ball surface. It reflects cooling by liquids or mixtures with respect to flow velocities. Contact resistance is included with respect to clearance and contact pressures [18].

- III. A full geometry is simulated. This respects a detailed geometry of the bearing. It enables a definition of the cooling properties, heat generation and heat transport to inner and outer ring. The model respects ball movements. The calculation requires a high amount of computation time.

In Figure 2 can be seen the results of full simulation of very short time of the bearing run. Low temperature difference is caused by the fact that temperature difference is defined by time derivation and friction losses. The results of thermal/flow computation are applied to structural model. As a result, the structural properties of the bearings are not influenced by the temperature change. Stiffness of the bearing is driven by defined parameter. All processed simulation helps with the macro-element definition for the macro-element model.
Figure 2. Full geometry simulation of bearing run in time 60 s, very low temperature difference in the groove $dT < 0.1\, ^\circ\text{C}$, can be seen, start temperature is 20\, ^\circ\text{C}, referred by equation (3).

2.1.2. Example 2 – Heat transport

The mechanism of a heat transport in the machine is defined by basic physic dependencies. The overall system must be decomposed to elementary cases which can be described and measured. Generated heat is transported mostly in the solid bodies of a structure by the conduction mechanism of the heat transport. These bodies are cooled by external liquids like cooling liquids, oil or air flow. Cooling is defined by convectional properties of a flow. Vital influence to the thermal behaviour and cooling of heat loaded parts has the parameter of contact heat resistance. This property describes the heat exchange between solid bodies, which are in surface-to-surface contact. A radiative heat transport mechanism can influence the geometry of a machine for instance by sunlight absorption. The radiative heat exchange between bodies in the machine is relatively low. The balance of the internal energy, thermal energy and power is defined as follows [5]:

$$\dot{U} = \sum \dot{Q} + \sum \dot{P}$$  \hspace{1cm} (2)

Then temperature change is:

$$m \cdot c_p \frac{\partial T}{\partial t} = \sum \dot{Q} + \sum \dot{P}$$  \hspace{1cm} (3)

where: $U$ – internal energy, $P$ – supply energy, discharging, $m$ – mass, $C_p$ – specific heat capacity, $T$ – temperature.

Convection between the rotating spindle and stator is defined:

A detail example of a heat transfers between a rotating spindle and a body of the ram can be seen in figure 3. The heat transfer coefficients were simulated with respect to the rotation of the spindle 500–3000 rpm. Surface properties and air flow were respected. The heat transfer simulation is influenced by mesh properties. The quality of generated mesh significantly influences the flow calculation. The correctness of mesh properties for the flow solution is characterized by the $y^+$ factor [16]:

- the viscous sublayer (1): $y^+ < 5$
- the buffer layer (2): $5 < y^+ < 30$
- the log-law region (3): $30 < y^+ < 200$

The simulation indicates the heat transfer coefficients 20–40\, W m$^{-2}$K$^{-1}$ on the ram-body surface and 50–80\, W m$^{-2}$K$^{-1}$ on the spindle surface. Overall near-wall $y^+$ function is 20–60 which signs suitable mesh quality and potential good quality of results. The predicted temperature difference and the heat transfer surface define the overall heat transfer between the spindle body, surrounding air and the ram body.
2.1.3. Example 3 – definition and validation of macro-element – cooling channel
Comparison of macro-element and simulation leads to macro-element definition and verification of macro-element outputs. Each element is defined by equations and verified by simulation with different boundary conditions. This approach provides fast computation and suitable accuracy of macro-model. The example of the definition of the elbow element can be seen:

Pressure loss (Pa) definition [19]:

\[ \Delta p = \xi_u \frac{\rho w^2}{2} \]  \hspace{1cm} (4)
\[ \xi_u = f(Re, D, r) \] \hspace{1cm} (5)

Thermal exchange definition based on [20]:

\[ htc_{conv} = \frac{\lambda D}{D} \] \hspace{1cm} (6)
\[ Nu_D = Nu_D(Re_D, Pr) \] \hspace{1cm} (7)

Temperature fields of macro-elements were stated:

\[ T(x) = T_w + \exp \left( -\frac{U \cdot R \cdot \Delta t}{c_p \cdot m} \right) \cdot (T_{in} - T_w) \] \hspace{1cm} (8)
\[ Q_w = (T(L) - T_{in}) \cdot c_p \cdot m \] \hspace{1cm} (9)

The results of the elbow-element simulation show a good match (figure 4). Deviation of results is lower than 10 %. The macro-element calculation based on elementary, empiric equations provides accurate results significantly faster than CFD simulation. A similar approach is used for the definition of other elements.
2.2. Validation
The results of the computation were compared with a test running of a real machine of machine parts. The quality of the assembly process of the main parts and the quality of the production process significantly influence the thermo-mechanical behaviour of the machine. Vital assembly connection in these machines is a rotational coupling by bearings. Highly precise spindle bearings required perfect geometry of surfaces and perfect assembly with respect to assembly instructions. This can significantly influence the temperature results (+/- 15 °C).

The test run verifies the correctness of the assembly process. The procedure also controls the vibration behaviour and overall functionality. Diagnostic functions of electric components also provide data for analysis. It is an electric current, which reflects the loading of electric motors. The temperature is analysed in specific, defined points of the machine.

The spindle precise bearings generate heat due to the preload and high revolution. Common temperature ratio is 40–80 °C. Overloading and overheating causes structural changes. Due to that, stiffness and durability of the bearing decreases.

The final transmission case is a similar example. Loading by external forces is different than loading of spindle bearings. Preload of the bearing is lower. The heat is generated in the gear. Heat is equivalent to the efficiency of the power transmission. Case of the final temperature is cooled by liquid circuit.

External sign of the effectiveness and the heat generation is the temperature of cooling liquids. The cooling capacity is dependent on the overall performance of the machine. Test running was performed by test rig. Running speeds are 1000 min⁻¹ for 0–30 minutes, 2000 min⁻¹ for 30–60 minutes, 2500 min⁻¹ for 60–300 minutes. Measured temperatures are shown in figure 5.

![Figure 5. Measurement of bearing temperatures during the spindle assembly test run.](image)

3. Sensitivity study and compensation

3.1. Sensitivity of design
A complex case definition is feasible after the evaluation of elementary cases. The previous predictions and evaluations provide vital data which support the complex case composition. You can see detail FEM model of a spindle with boundary conditions (figure 6). The results were compared with the measurement. Sensitivity study was performed. It means that the results of the thermal load and displacements were compared with respect to the variation of the changed boundary conditions.

Modal properties are also influenced due to the changes of non-homogeneous temperature fields. It is caused by the time-dependent variations of pre-stressing, which is influenced by temperature elongation. Simulation allows to change the pre-stress and find the dependency of modal properties and temperature field. As written above, dependency of bearing stiffness on temperature change is not included.

Boundary condition reflected the running option of the real machine. The test running was stated to be 3600 s with respect to the computation capacity. Boundary conditions of heat induction, heat transfer and mass flow were described.

The described virtual model was tested by the amount of possible boundary conditions as can be seen in table 2.
3.1.1. First set of simulation
Set of boundary conditions and run time were stated to observe the behaviour of the model simulation. The boundary conditions were stated with respect to required data. Input revolution characteristics are similar to the measured test run. The test run \(z_0\)–\(z_3\) show the steady-revolution run. Variation of the heat transfer coefficient simulate the isolation between inner ring of the bearing and the spindle.

**Table 2.** Boundary conditions for the simulation.

|          | \(z_0\) | \(z_1\) | \(z_2\) | \(z_3\) | \(z_{10}\) | \(z_{11}\) | \(z_{12}\) | \(z_{20a}\) | \(z_{20b}\) | \(z_{20c}\) |
|----------|---------|---------|---------|---------|-----------|-----------|-----------|-----------|-----------|-----------|
| Bearing 12 | w       | 300     | 400     | 500     | 600       | 300       | 300       | 300       | 300       | 600       | 800       |
| Bearing 34 | w       | 300     | 400     | 500     | 600       | 300       | 300       | 300       | 300       | 600       | 800       |
| Bearing 5  | w       | 150     | 200     | 300     | 400       | 150       | 150       | 150       | 200       | 400       | 600       |
| Bearing 6  | w       | 200     | 300     | 500     | 700       | 200       | 200       | 200       | 200       | 500       | 700       |
| Final gear | w       | 300     | 400     | 400     | 300       | 300       | 300       | 300       | 200       | 300       | 400       |
| F.g. case  | w       | 100     | 150     | 200     | 250       | 100       | 100       | 100       | 150       | 200       | 250       |
| Tool      | w       | 120     | 120     | 120     | 120       | 120       | 120       | 0         | 0         | 0         |
| Htc       | w m\(^{-2}\) K\(^{-1}\) | 0       | 0       | 0       | 0         | 400       | 600       | 800       | 1000      | 1500      | 2000      | 2500      |
| Revolutions | n min\(^{-1}\) | 100     | 125     | 150     | 200       | 100       | 100       | 100       | 1000      | F(t)      | F(t)      | F(t)      |
| Time      | min     | 0-      | 0-      | 0-      | 0-        | 0-        | 0-        | 0-        | 0-        | 0-        | 0-        | 0-        | 0-        |

**Figure 7.** Tool displacement, test run \(z_0\)–\(z_3\), dependency on the rpm of the spindle, differences of dilatation is around 25 %, which is proportional to the revolutions and friction losses.

**Figure 8.** Tool displacement, test run \(z_0\)–\(z_{12}\), steady rpm of the spindle, deviation < 2 %.
Figure 9. Average temperature of the spindle, low effect of the heat transfer coefficient can be seen, temperature deviation < 5 %.

Figure 10. Bearing temperature, dependent on the heat transfer to the spindle, temperature deviation 9 %.

Results in the figures 7 and 8 show the dependency of structural changes during the work regime. Rise of the revolutions causes rise of the heat load. Higher temperatures cause higher displacements. Isolation between the inner rings of the bearings and the boring spindle has relatively low effect. It is shown in the figures 9 and 10.

3.2. Compensation of elongation

Elimination of the thermal elongation is a highly required solution. The compensation of the thermal displacements of the boring spindle is not a trivial issue. The spindle is a rotating part with many requirements. Stiffness requirements and narrow shape restricts a great number of possibilities for improvements. Also, the dynamic and modal properties restrict the shape intervention. Current work operates with three principles which solve the problem:

a/ instant precise measurement of deformation

Precise measurement of tool position should be a solution for many problems caused by deformation of structure. This accurate measurement in the environment filled by cooling liquids, steel chips etc. is almost impossible.

b/ prediction of deformation effected in driving instruction

Accurate, fast prediction is described above. Definition of fast computation with required accuracy for the instant prediction have to be based on simply equation, supported by instant measurement of temperatures, stresses etc. Computations are based on the temperature measurement. This shows the requirement for accurate, fast temperature measurement in complicated parts of a machine:

$$\delta = \sum_{n=1}^{m} a_n \ast T_n$$

(10)

where $\delta$ – calculated deformation, $T$ – measured temperatures, $a$ – calculated coefficients, $m$ – number of used sensors.
c/ direct compensation with no external instruction

Sensitivity study identified the crucial parts which influence the main deformation of a machine. Inclusion of compensation parts into the structure decreases a specific elongation. Inclusion of composite parts with extremely low expansion coefficients has a potential to decrease the overall accuracy [21]. Specific structural properties significantly influence the thermo-mechanical behaviour of a machine (the thermal and structural symmetry, the place of the heat load, the design of the cooling features). Inclusion of specific, compensation part can decrease the elongation effect. Initial design simulation of this feature indicates the possibility to decrease elongation in 0.2 mm, initiated by temperature difference $dT = 20$ °C (figure 12). The included parts must not influence the overall design, structure and the mechanical properties of the spindle assembly.

Figure 12. Compensation part simulation, temperature difference $dT = 20$ °C, negative elongation 0.2 mm.

4. Conclusion and outlook

Simulations of thermo-mechanical behaviour of machines provide highly potent data for the development of the high performance milling machines. Thermal stability and precision is a crucial demand. Research shows the approach in the field of thermo-mechanical simulations and predictions. The sensitivity study described the methodology for the identification of critical parts with a high thermal load and significant deformations. Partial simulations provide useful data of component behaviour. This data has been used for the complex simulations. Verification and validation of the methodology by the comparison with measured data is a vital part of the described approach. Measured and validated data of the bearing temperatures significantly influence the overall deformations. Prediction of this behaviour leads to the prediction of overall thermal behaviour and precision of a machine.

Inclusion of the new compensation approaches into the overall simulations can identify the new potential solutions. The new technologies like topology optimization, 3D metal print or carbon fibre reinforced polymer (CFRP) are suitable for the accuracy enhancement of the machine tools. CFRP inclusion is a highly potential way for the enhancement of the thermo-mechanical behaviour. The work summarizes the goals in the research focused on the enhancement of the thermo-mechanical behaviour of the machine tools.
5. References

[1] Mayr J J, Jedrzejewski E, Uhlmann et al. 2012 Thermal issue in machine tools CIRP Annals - Manufacturing Technology 61 771–791

[2] Janda P and Polák R 2016 Virtual prototyping and optimization of heavy machine tools Proceedings of the 26th DAAAM International Symposium 2016 Vienna pp 967–973

[3] Marek V 2018 Sensitivity analysis and validation of a thermo-mechanical model of a spindle Proceedings of the 29th DAAAM International Symposium 2018 Vienna pp 703–708

[4] Bergman, T. and Incropera F 2011 Fundamentals of Heat and Mass Transfer (Hoboken: Wiley)

[5] Gebhardt M 2014 Thermal Behaviour and Compensation of Rotary Axes in 5-axis (Zürich: ETh)

[6] Züst S, Pavlíček F, Fischer L, Weiss L and Wegener K 2016 Thermo-energetic modelling of machine tool spindles with active cooling based on macro models International Journal of Mechatronics and Manufacturing Systems 9 197–214

[7] Züst S 2015 Model based prediction approach for internal machine tool heat sources on the level of subsystems Procedia CIRP 28 28–33

[8] Michaliček M 2013 Prediction of working accuracy of CNC machine tools (Brno: Brno University of Technology) (in Czech)

[9] Mindl J, Horeš O and Smolík J 2013 Advanced temperature compensation of portal machining center MM Průmyslové spektrum 10 131043 (in Czech) Available: http://www.mmspektrum.com/clanek/pokrocile-teplotni-kompenzace-portaloveho-obrabecich-centra.html

[10] Holkup T, Cao H, Kolář P, Altintas Y and Zelený J 2010 Thermo-mechanical model of spindles CIRP Annals 59 365–368

[11] Weber J and Weber J 2013 Thermo-energetic analysis and simulation of the fluidic cooling system of motorized high-speed spindles The 13th Scandinavian International Conference on Fluid Power Linköping pp 131–140

[12] Vyrobal J 2010 Using the spindle cooling temperature as a tool for compensating the thermal deformation of machines Acta Polytechnica 50 19–22

[13] Svoboda O 2013 Solution of thermal deformations of machine tools MM Průmyslové spektrum 7 130734 (in Czech) Available: http://www.mmspektrum.com/clanek/reseni-tepelnych-deformaci-obrabecich-strojui.html

[14] Testing of CNC machine tools 2014 MM Průmyslové spektrum 658–660 (in Czech) Available: http://www.mmspektrum.com/content/file/CNC_ukazky_Cz/9.3.pdf

[15] Marek J 2010 Design of CNC Machine Tools (Prague: MM publishing) (in Czech)

[16] SIEMENS AG. Flow Solver Reference Manual Simcenter 12. Plano: Siemens Product Lifecycle Management Software, 2017

[17] SIEMENS AG. Thermal Analysis User's Guide. Plano: Siemens Industry Software, 2017

[18] Thermal Contact Resistance 2011 DOI: 10.1615/AtoZ.t.thermal_contact_resistance

[19] VDI-Wärmeatlas 2006 (Heidelberg: Springer)

[20] Marek V and Hájíček Z 2017 Thermal simulations based on macro-models Proceedings of the 28th DAAAM International Symposium 2016 Vienna pp 627–634

[21] Sedláček F and Lasova V 2017 Design and optimization of composite parts using numerical simulations International Conference on Mechanical, System and Control Engineering (ICMSC) DOI: 10.1109/ICMSC.2017.7959434

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