THERMAL DEFORMATIONS OF MILLING CENTER
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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 the produce activity. Thermal loading influents productivity and precision of a 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. All these methods have common disadvantages, which include the need for a skilled engineer, hardware and software. In general, it causes high cost of a computation. The reduction of costs is solved by a new tool, which uses simple macro-elements with predefined, parametric properties. Reduction of thermal displacement is also a crucial task. Sensitivity study, based on complex case study is able to identify features with significant influence to overall deformation. Complex case consists of detail subcase analysis. Identified parts require modifications for the decreasing of deformations. Results are compared with the new productive computation method based on macro-models. Combination of methods defines productive methodology, which lead to fast prediction and accurate simulation.

KEYWORDS

Thermal deformation, computed fluid dynamic, final element method, macro element method

INTRODUCTION

Machine tools are highly sophisticated mechatronic systems enabling manufacturing processes to a given precision. A machine tool’s precision strongly depends on its thermo-elastic behaviour. 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, based on Bergman [1]. One of the main factors in mastering the thermal behaviour of machine tools is effective cooling, which is described by Mayr [2]. 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. Direct cooling of cutting tools is used in almost every cutting process. It provides cooling of the tool and lubricates the cutting area [13,16]. 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 [4]. 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. For this purpose, a method based on elementary elements for the fast evaluation of the thermal behaviour of fluid based cooling systems. The heat loading of the main part causes heat displacements which are a significant factor in the precision of machining. Displacements of the spindles are also examined in this article.

STATE OF THE ART

The modelling of an actively cooled machine tool spindle unit requires at least three steps: First, the heat sources must be predicted depending on the operational point. They establish the boundary conditions for the following simulation. Second, the fluid flow in the cooling duct must be simulated. In the third step, the heat transfer problem must be solved, including conductive and convective heat transfer in the spindle structure and the coolant. The current state of these methods, as well as an implementation is presented in [2,4,5,16].

Basic points of the topic

Prediction of thermal effects is an essential requirement for design these machines. Process is influenced by time consumption, budget, and required accuracy. Process should solve thermal displacements, durability, technology and structural properties. Design and calculation of heat loaded machine solves many questions. Decomposition of complex cases could help with fast precognition and evaluation of the effect. Known and unknown boundary conditions must be evaluated by measurements. Precision of computation is not a trivial question, because of the high costs of computation.

QUESTIONS

The design process of a heat loaded machine must solve many questions: How to get data with low costs? What level of precision is required? What heat transfer coefficients are known and unknown? What loads and heat losses can be identified? How to simulate thermal effects in machine tools? How to evaluate thermal effects? How to compensate dilatations?

Design of a heat loaded machine is a cycle of these points:

- Basic calculation, prediction
- Design, problem solution CAD
- Simulation FEM/CFD
- Measurement, evaluation

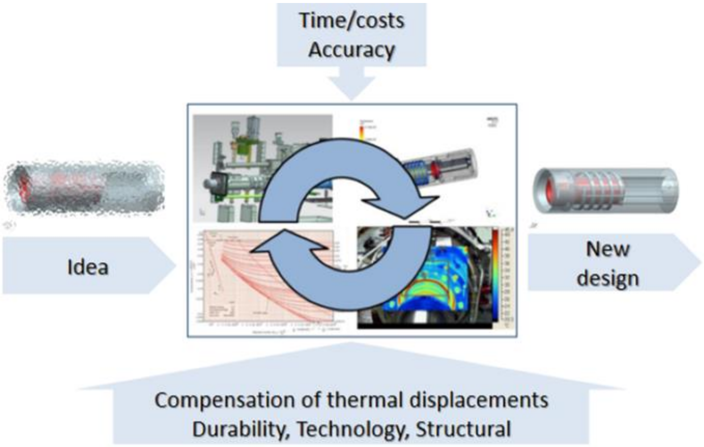

Fig. 6 Design process with cycle of base points

SIMULATION - COMBINATION TO GOAL

A new design process was developed with implementation of new methods. The simulation and design processes were improved with macro element support. Calculations and simulations should be implemented in every design of a machine. This work deals with two statements: prediction and simulation. High precision, accurate CFD/FEM simulation at the beginning of designing is an expensive step with low value results. The goal of improvement is a combination of prediction by macro-element calculation and simulation by CFD/FEM. Macro-model computation provides very fast predictions of thermal transfer. It is a significantly faster computation. It is not a full substitution of CFD simulation in this context. It provides fast, basic data for basic predictions in the design process, as can be seen in Figure 2. A disadvantage is the same as with CFD – known/unknown coefficients. New Macro-model computation provides very fast predictions of thermal effects. It is a significantly faster computation. Described Macro model computation for cooling channels is developed at ETH university in Zurich. It is thermal computation based on simply equations. Comparison of methods is in the Table 1. Macro-elements are distinct elements, defined by elementary equations. The properties of the macro-element depend on the properties of the fluid, the duct geometry and the operational point. These dependencies determine pressure losses and heat transfer which are the two significant factors in cooling circuits. Implementation of macro-element calculation rapidly decreases computation time in beginning of design. Crucial problem is definition of each element. A difficult case is divided into simple cases which could be solved, measured and verified. Analysis of basic elements are included. [10] Table1 shows, that implementation of macro-element calculation rapidly decreases computation time in beginning of design. This computation provides suitable data (result deviation <20%) before detail CFD/FEM simulation.

	Prepare time	Comp. time	Temp. Comp.	Result deviation	Costs
CFD	1hour	>600s	full	<5%	High
Macro-model	1/2hour	<1s	partial	<20%	Low

Table 8 Comparison of CFD/FEM simulation and macro-element calculation [16]

ELEMENTARY CASE ANALYSIS

Coefficients of heat transfer are discussed because of the high ratio of values. Boundary conditions of 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 turbulent model. Essential properties in these calculations are wall roughness, advection schemes, etc. Details of the elementary case evaluation were published [15] A complex case is decomposed into basic features like housing of the bearing, the bearing, and the cooling channel. These features are examined in isolated cases. The divided features represent basic macro-elements, represented in Figure 3. Thermal effects in simple bodies or surfaces are able to be described by basic equations available in Marek [16] and VDI [3].

Ball bearings

Methodology of simulation and simplification of BEARING was stated. I have analysed three FEM methods, based on simplification.

I. Heat load is simulated by the boundary condition of heat load directly to the inner and outer rings.
II. Bearing is replaced by revolved geometry
III. Full geometry is simulated

You can see comparison of results. Simulation of full geometry required extremely amount of computation time. Trivial BC to the rings ignore the cooling properties. Revolved model cannot describe structural properties. All processed simulation helps with Macro-element definition for macro-element model.

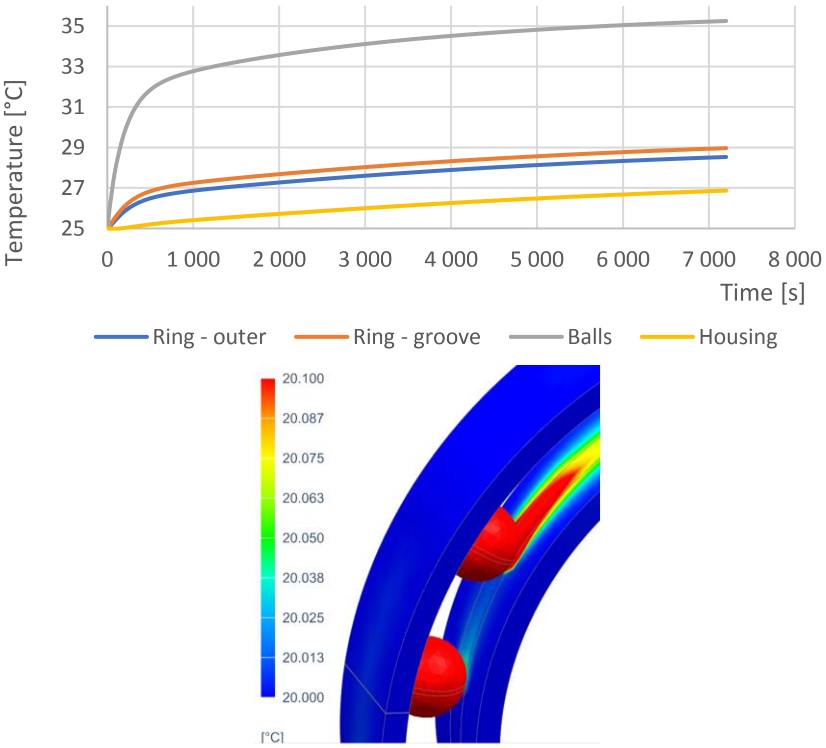

Fig. 7 Detailed heat transfer simulation of a ball bearing, transient time-dependent temperatures

General heat processes

You can see analysis of heat transfer between rotating spindle and housing. Solutions were used for complex FEM solution and macro-model definition. Simulation was performed with rotating spindle body. Many CFD factors were included. First picture describes y+ parameter which characterise potential accuracy of results. Second one is result of heat transfer coefficient. Results are included into complex case solution.

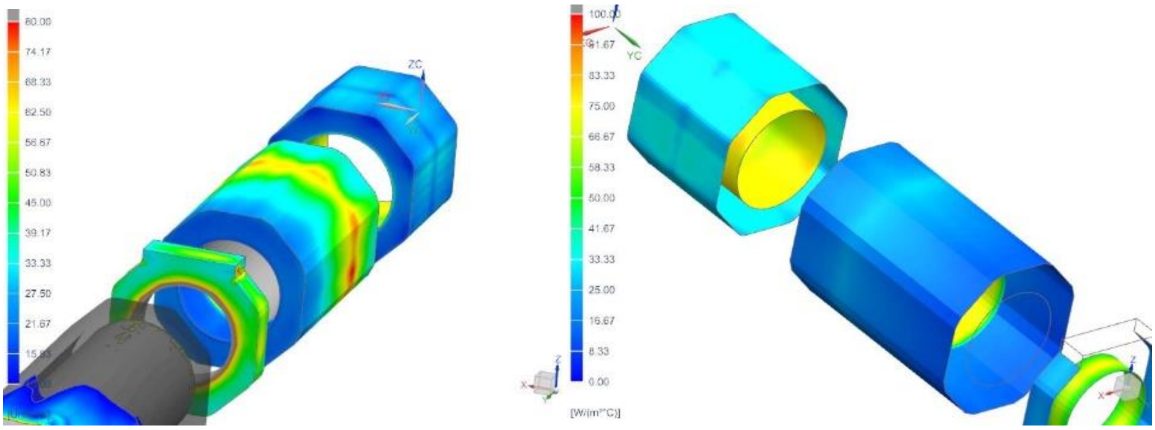

Fig. 8 CFD simulation of inner air of the spindle assembly, y+ factor on the left, heat transfer coefficients on the right

Analyse of Elements of DuctDesigner software

The third detail shows macro-element of fluid cooling circuit. This analysis is performed for the enhance of the accuracy of macro-element computation. Elements of macro-model computation software were analysed. Each element was empirically calculated and simulated. Ansys CFX and NX CFD calculation were used. The goal was to tune each macro-element calculation for better precision of the calculation. One of the results is shown in the picture bellow and the comparison of results is in the chart.

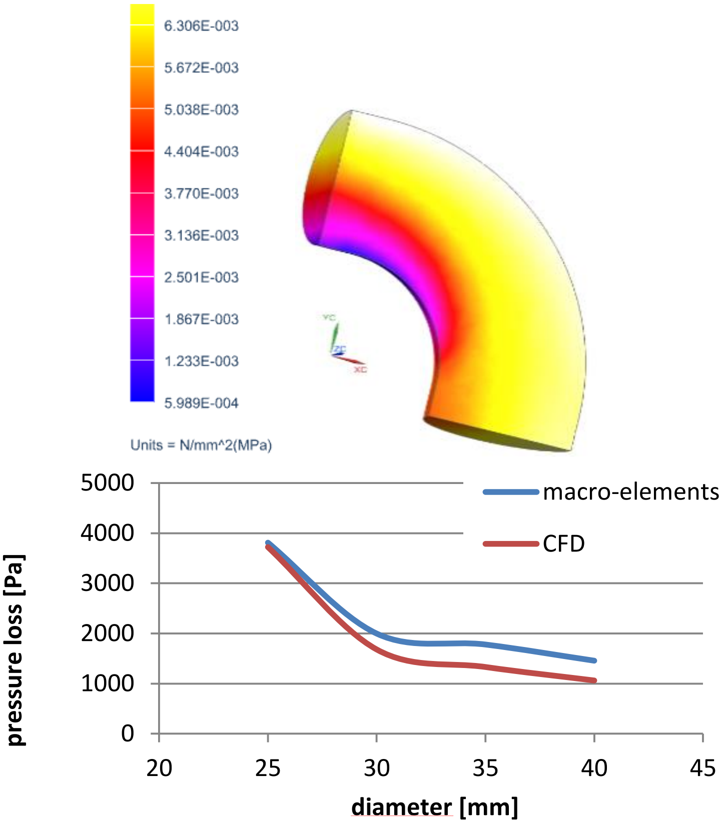

Fig. 9 Analysis of the channel elbow, CFD on the left, diameter dependent pressure loss on the right

Complex case - FEA

Complex case definition is feasible after the evaluation of elementary cases. The previous predictions and evaluations provide vital data, which supports the complex case composition. You can see detail FEM model of a spindle with boundary conditions in the Figure 5. Results were compared with measurement, processed by Skoda Machine tools [12]. Sensitivity study was performed. It means that the results of thermal load and displacements were compared with regard to variation of changed boundary conditions.

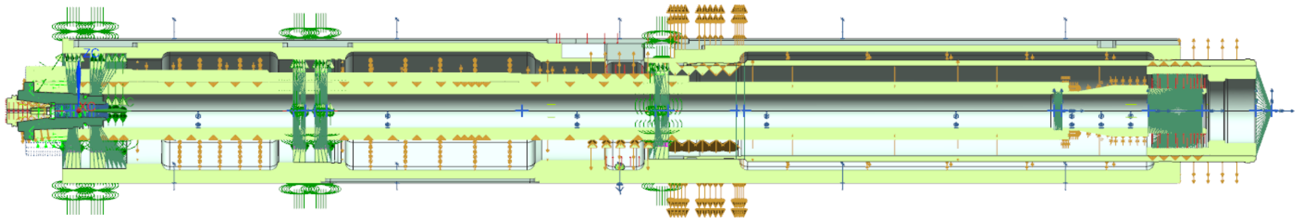

Fig. 10 Complex FEA analysis of the spindle assembly

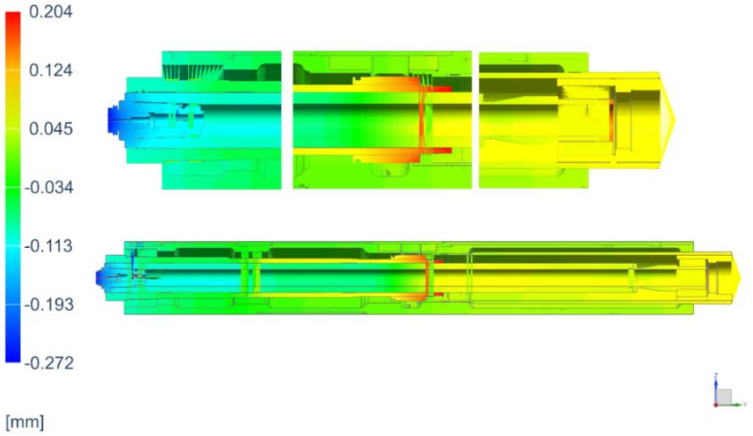

Fig. 11 Results of complex simulation, thermal deformation dependent on heat load and time, processed by Marek [14]

COMPLEX CASE - BASED ON MACRO-ELEMENTS

The same complex case of spindle was designed, based on macro-models. The previous predictions and evaluations provide vital data which support the complex macro model composition. Detail boundary conditions are also included. Heat generation in the bearing, heat transfer in the fluid space, heat transfer on the interfaces dependent on contact pressure [1,6,3]. Macro-model shows partial elements connected by equations.

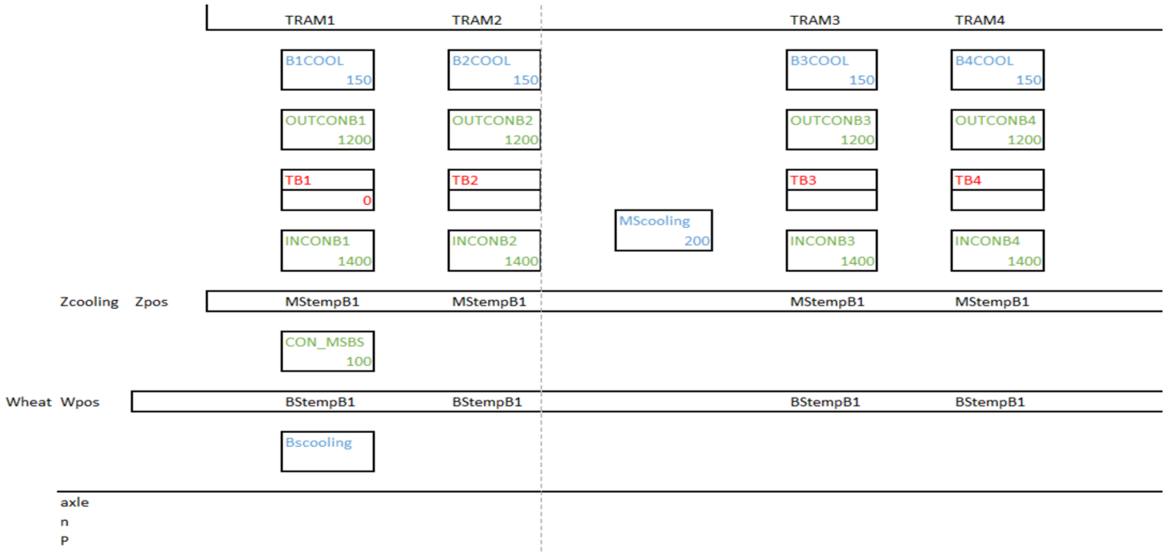

Fig. 12 Scheme of a spindle imaged by macro-model configuration

Thermal loading of a spindle of a milling machine

The complex case presented here is essential for current research. Research of thermal effects in a head stock assembly is vital for the solution of the problem of thermal dilatation. Two sources of information are examined. Heat transfer simulation of the assembly of the head-stock is performed. Temperature of body depends on temperature of inner parts. It is possible to develop algorithm for calculation of temperature of the spindle with dependency on outer temperatures. Detail examination of thermal behaviour is required because of that, as shown by [9,10,11]

The processes described above are used to analyse a spindle unit. The section view in Figure 7 shows the main features of a spindle of a large horizontal boring machine. The main heat sources can be identified: ball bearing, transmission box, etc. Vital deformations are identified: dilatation in y, z, w axes. Heat sources are identified: main spindle bearing referred by [8,9], final transmission, electric components. Cooling effects are pointed out: cooling liquid circuit of final transmission, cooling liquid on centre of the spindle, convection cooling of environment,

conduction in spindle body, radiation cooling of spindle body. Thermal resistance of surface contacts is one of the other effects. Compensation of a displacements of the ram is already used. A rod made of material with different thermal expansion (Invar) is used. A compensation of displacements of the boring spindle is required.
Thermal compensation of the boring spindle is an exceptional issue. The spindle is a rotating part with many requirements. Stiffness requirements, narrow shape restrict many possibilities for improvements. Also the dynamic preferences restrict shape intervention. Direct measurement by external probes ensures exact positioning. Contactless measuring by laser or ultrasonic waves can also protect positioning. Fanuc company use AI for prediction of deformation based on measurement on the body of a machine. Suitable principles of compensation are: direct measurement of deformation, prediction of deformation and direct compensation, shown by Marek [14]. A promising method is non-direct measuring. It is a method based on measurement of dependent values. It is a temperature measurement of the specific points of the body coupled with a computation algorithm. The algorithm is based on the elongation dependency on the temperature. This provides elongation computed by temperature measurement. It is possible to use temperature measurement of the bearings, measured temperatures of the nonrotating parts, etc. The algorithm for prediction of deformation based on macro elements is in the develop phase. Sensor implementation, processing of dependent values and parameters, compensation based on a mathematic model are methods which are included in Industry 4.0 methodology.

CONCLUSION AND OUTLOOK

Macro-element method is integrated to the simulation process. Elementary cases were analysed and evaluated. Thanks to complex case complexation, the sensitivity study could be processed. Possibilities of thermal displacement compensations were analysed and complex Macro-element method is just in the develop phase. Macro-element method will be fully integrated into the computation process this year and results will be compared with the complex measurement. Opportunities for this method will be identified. Promising results validate the new methodology.

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