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CONCEPT OF INTEGRATING A HYBRID THERMAL ERROR COMPENSATION INTO AN EXISTING MACHINE TOOL CONTROL ARCHITECTURE

Thermal error compensation via a numeric control (NC) system is a proven option for upgrading the precision of existing machine tools. The main advantage is the generally cost-effective application, as no changes to the machine design are necessary. Since many modern machine tools are equipped with standard numeric controls along with additional functions and integrated temperature sensors in the machine, compensation methods such as a characteristic diagram (CD) based compensation can be implemented. To increase the applicability and reliability of this CD regression method, a hybrid model approach with a virtual thermo-elastic finite element (FE) machine model and a real-time computable structural model of a machine tool was developed. The structural model uses model order reduction to calculate the current load case in real-time using continuously recorded machine data (motor current, axis position, temperatures). It acts as a virtual monitoring application to check, whether the current machine condition still matches the current CD based prediction. If the current load case is not suitable to the active CDs or any other stored CDs, the generation of new CDs is automatically triggered. In this process, the thermal boundary conditions for the FE simulation are generated for that respective load case and CDs are calculated to replace the active ones in the NC. In this article, the integration of the hybrid compensation method using an FE model and a structural model of a machine tool is methodically demonstrated. The main focus is on the integration of different software and hardware architectures and their interaction.

1. INTRODUCTION AND MOTIVATION

The manufacturing accuracy of machine tools is significantly influenced by thermal effects that cause displacements on the machine axes due to the heating of machine components from internal sources or environmental influences. For this reason, there is a broad interest in research towards methods for thermal error reduction, particularly in the manufacturing industry [1]. One of many interviews conducted by Regel et al. among

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machine manufacturers and users, showed that thermally induced production errors on workpieces are a major concern [2]. Both Mayr [1] et al. and Gebhardt [3] have shown that the thermal behaviour of the machine must be analysed and understood for implementing successful thermal error avoidance and compensation strategies.

The main idea behind the introduction of thermal compensation in machine tools is to increase accuracy in the production of components in an energy-efficient and cost-effective manner [4] by correcting the predicted thermal drift in the Numeric Control (NC) program or by applying a position offset while the machining process is running [5], as it is also successfully implemented for geometric modelling, e.g. [6], and dynamic modelling, e.g. [7]. This reduces the need for design measures (e.g. cooling systems) for the machine or the environment (e.g. climate chamber) in order to reduce the undesirable thermal effects. This is because the measures for thermal error avoidance often lead to additional design effort and increased energy consumption, which increases the fabrication and operating costs of the machine. With compensation, on the other hand, the thermal deformation is present but continuously predicted and subsequently reduced. However, compensation as a controlled system requires that the thermo-elastic state of the machine is monitored by temperature sensors or by direct measurement of displacements [8] and that this data is provided to a compensation model. This requires a corresponding architecture and a communication interface in the machine control system.

According to the state of the art, several compensation methods for thermal errors on machine tools have been developed and tested [8–13]. Beside other methods that use for example learning algorithms [14–19], two main compensation methods with different approaches are considered in this article:

- Black box method: Characteristic diagram (CD) based compensation [20–23] and
- White box method: Structure model-based compensation [24–26].

Black box methods, which include characteristic diagram-based compensation as an example of regression analysis, are commonly data-driven approaches based on existing datasets of several machine load cases that are interpolated, e.g., by a high-dimensional characteristic diagram, also called characteristic map. Using suitable input variables, such as temperatures and axis positions, a vector for the displacement between the tool center point (TCP) and the workpiece is calculated with the help of the CD. A CD is usually a multivariate, piecewise-linear regression table, though nonlinear basis functions such as radial basis functions or higher order B-splines [27] may also be used. The computed vector represents the thermal displacement and is applied to the NC position as an offset. The main advantage of this approach is the possibility of offline generation of training data of relevant machine load cases from high-resolution simulation models of the machine [28]. The more precisely the real machine state matches the simulated training data for teaching the CDs, the more accurate is the compensation. Extrapolation to unknown load cases is generally unreliable, which limits the usefulness of CD based compensation in applications with many, frequently changing load scenarios, such as job-shop production.

In contrast, white box methods, which include structure model-based compensation, usually simulate the thermo-elastic interactions within the machine in a slower thermal real-time (few minutes). The structure model employs model order reduction (MOR) techniques, based on Krylov-subspace methods. From the original finite element (FE) simulation model of a machine, an input-output model is created, which is subsequently reduced to a lower-dimensional reduced order model (ROM). Despite its smaller size, the simplified ROM captures or approximates the key characteristics of the machine while achieving substantial reductions in computational time. This ROM updates the calculated machine state in short intervals using the machine's control data (including axis position, speed and ambient temperature) as input and provides the computed displacements via a kinematic model [29]. The advantage of this method is that it can simulate any sequence of thermal loads. However, the modelling effort for the structure model can be high for a sufficient accuracy and there are always issues regarding unknown initial conditions and temperature states that drift away from the real machine state due to error propagation.

The aim of this article is, therefore, to present a methodology to combine the advantages of both, CD based and structure model-based compensation in an existing control architecture of a commercially available machine tool as a hybrid methodology [25, 30]. In addition, advantages, hurdles, and possibilities for transferring the methodology to other machine types and technical processes are discussed. The methodology presented in this article is tested on a DMU 80 evo five-axis machine tool with eight integrated temperature sensors. The prediction quality can be estimated with the help of a monitoring application running in the background, which checks that the active CDs are suitable for the current machine load case. The monitoring application, as the name suggests, 'monitors' the machine and is responsible for the realization of another set of tools to perform validity checks on the current CDs and to support deciding when new CDs are required during machine operation. This assessment is made with the help of a parallel-running structure model [24]. It calculates temperature values for the current load case on the machine. Then these values are compared to the temperatures with which the active CDs were trained to determine if they will reliably predict the corresponding displacement or if new CDs are needed. Rather than simply using the values from the few physical temperature sensors, this approach enables a more precise comparison of the machine's temperature fields. The movement of the machine axes and the influence of the ambient temperature within a defined period of time (time increment) is referred to as a machine load case. Additional influences such as the use of cooling lubricants or the activation of support systems can also be taken into account in a load case. This new hybrid compensation method is primarily designed for use in an industrial environment for improving productivity and machining accuracy in job-shop applications.

The following chapters describe the main steps in implementing the hybrid compensation. Chapter 2 focuses on the automated generation of boundary conditions (BC) for a thermo-elastic FE-model of the machine. The calculated results from the simulation are used as input for the creation of the CDs, as presented in Chapter 3, which then perform the compensation via a suitable strategy in the machine control system. The procedure to utilize the CDs to offset the tool position in the control system is described in Chapter 4. Finally, Chapter 5 presents the overall integration of the hybrid compensation and Chapter 6 summarizes the results. The overall task of implementing the hybrid compensation on a machine includes the main components of the "thermo-elastic FE-model", a "structure model" for predicting the temperatures on the basis of machine load data, the "software tools for generating boundary conditions and characteristic diagrams" and the "integration into the NC of the machine" are described in the following chapters. More details regarding the theoretical concept behind the hybrid modelling approach are described in Friedrich et al. [30], providing a foundation for the integration of the concept presented here.

2. THE GENERATION OF COMPENSATION MODEL TRAINING DATA VIA THE ANALYSIS AND SIMULATION OF MACHINE LOAD CASES

To generate CDs, a set of training data for various machine load cases is calculated using a parametric thermo-elastic FE model. In the first step, some basic load cases for initial CDs of the machine's thermo-elastic behaviour are simulated in order to obtain a good general compensation model as a default. For these load cases, the maximum feed of each machine tool axis is used, because this approach usually lead to the maximum deformations caused by waste heat generation (for the given ambient state). In this process, all individual axes are moved one after the other at maximum speed over the entire axis range until a steady state is reached, which is done both in the FEM simulation as well as experimentally on the actual machine tool [30]. This thermal load is first applied without the use of cooling lubricant and without a cutting process. In order to make the model parametrization as simple as possible, a thermally stable initial machine state and a constant ambient temperature during the measurement should be ensured, so that internal and external thermal influences can be studied separately. Measurements in the air-conditioned environment of a climatic chamber are best suited for this [8]. Measurements should be performed until the machine reaches a (nearly) stationary thermal state, which, depending on the active heat sources, takes between 6 and 24 hours on the DMU 80 evo. For parametrization, simple load cases are used with one or few active heat sources. Job-shop conditions are not useful for parametrization but serve well for independently validating the model parameters after optimization.

These measurements are then used to parametrize the FE model by comparing the measured and simulated temperatures and displacements. Repeated simulations with iteratively adjusted boundary conditions are performed until a good agreement between simulated and measured temperatures and displacements is achieved. This step is the most complex and time-consuming during modelling and must be (at least partially) repeated for each machine type. The procedure for this is described in detail in [28] on the example of the DMU 80 evo.

For each individual axis, a set of thermal boundary conditions (BCs) (Fig.1) is assigned in the FE model, which defines the transient heat input from heat sources and the heat dissipation from cooling and convection in order to accurately simulate the thermal behaviour.

Figure 1 schematically shows the set of heat sources for a linear axis with ball screw drive (BSD) and linear guides, as present in the demonstrator machine DMU80 evo, exemplarily for the *X*-slide. The moving assembly is placed on four guide carriages and moves on two linear guide rails. It is driven by an electric motor and a BSD. The BSD spindle is mounted on roller bearings (fixed and floating bearings) and is driven by a toothed belt drive, where a maximum speed of 0.833 m/s is possible.

The enclosure was not taken into account in this FE model. The enclosure causes a different temperature in the working space than outside the machine. This was taken into account by different temperatures and heat transfer coefficients in the working space. The workspace was segmented into several partial areas and these individual segments were assigned their own boundary conditions (temperature and heat transfer coefficient).

Heat sources are defined on volumes or surfaces where heat flows/fluxes are introduced into the components, e.g., due to friction or electrical losses (see Fig. 1, left), and are modelled as heat flows or heat flow densities in the simulation. Once the parametric values have been assigned and the simulation model has been validated with the measurement data, the BCs for the FE model can be provided for unknown load cases using time-averaged variables with a factor between 0 (standstill) and 1 (maximum axis speed). Since only conduction heat flows, defined temperatures and convective heat transfers can be used as boundary conditions in the thermal FE model, the necessary boundary conditions cannot directly be obtained from the G-code (NC machining program). These BCs must therefore be calculated from an analysis of the G-code (Fig. 2).

X-Axis (Boundary Conditions – Heat Sources)

Guide Rails (GR)

BC name	*Value*	*[Unit]*
Top		
GR_T_1	10.5	W
...	...	...
GR_T_10	10.5	W
Bottom		
GR_B_1	8	W
...	...	...
GR_B_10	8	W

Guide Carriages (GC)

BC name	*Value*	*[Unit]*
GC_X_LT	13.5	W
GC_X_LB	13.5	W
GC_X_RT	13.5	W
GC_X_RB	13.5	W

Ball Screw Drive (BSD)

Boundary Conditions-(BC) name	*Value*	*[Unit]*
Fixed_Bearing_1	132000	W/m³
Fixed_Bearing_2	132000	W/m³
Loose Bearing	36000	W/m³
Ball-Screw-Drive bracket	28	W
BSD-Spindle Segments		
BSD_1	1.2	W
...	...	...
BSD_10	1.2	W

Heat Loss Motor

BC name	*Value*	*[Unit]*
Motor X	108450	W/m³

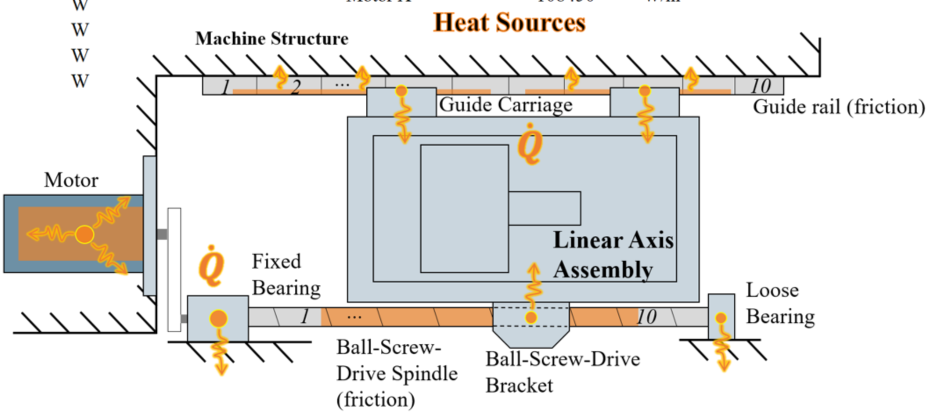

Fig. 1. Parametric boundary conditions for a linear axis (example)

To create physically boundary conditions for the FE model, an newly developed tool called “histogram generator” is utilized. This tool generates machine load data and visualizes it in histograms (Fig. 3) showing the load case over a specified time period for each axis. This is done by analysing real-time machine trace data such as axis speeds and axis positions (Fig. 2). For the automated calculation and transfer of the boundary conditions from experiments or structure model simulations to the FE model, a time-averaged value is obtained for each individual machine axis over a defined time increment using the histogram method. Values between 0 (standstill) and 1 (max. feed) are defined as global factors for each machine axis as shown in Fig. 3. The values for the heat flows are known for the maximum speed from the initial parameterization and are interpolated for lower speeds. In order to determine a suitable interpolation function, measurements at lower speeds can be used and compared to maximum speed.

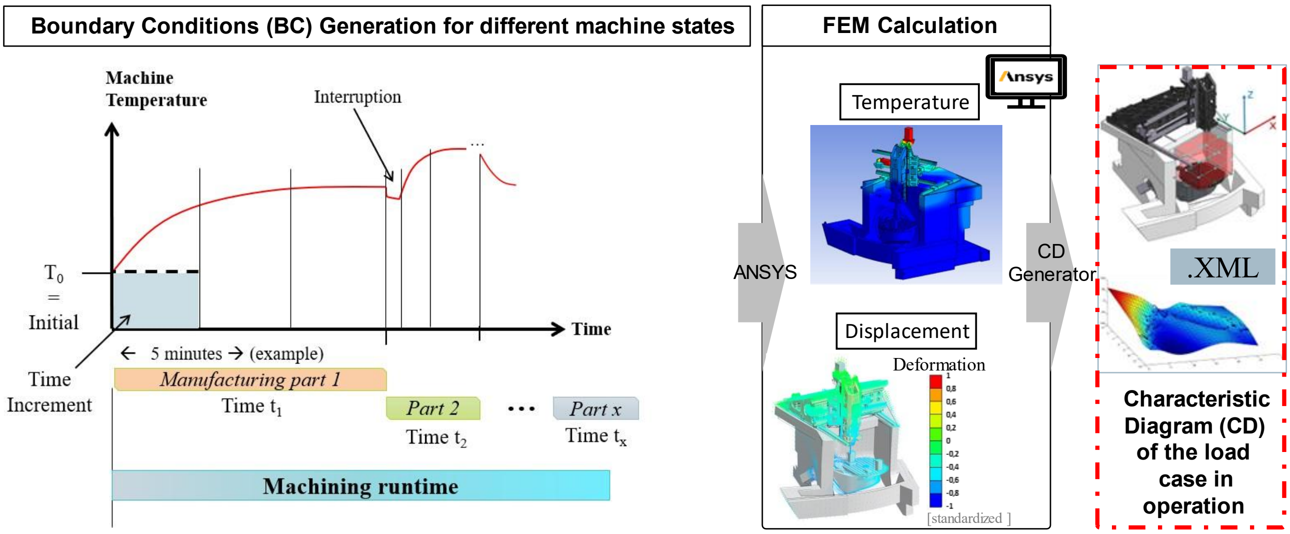

Fig. 2. General overview for the creation of characteristic diagrams using FEM for unknown load cases

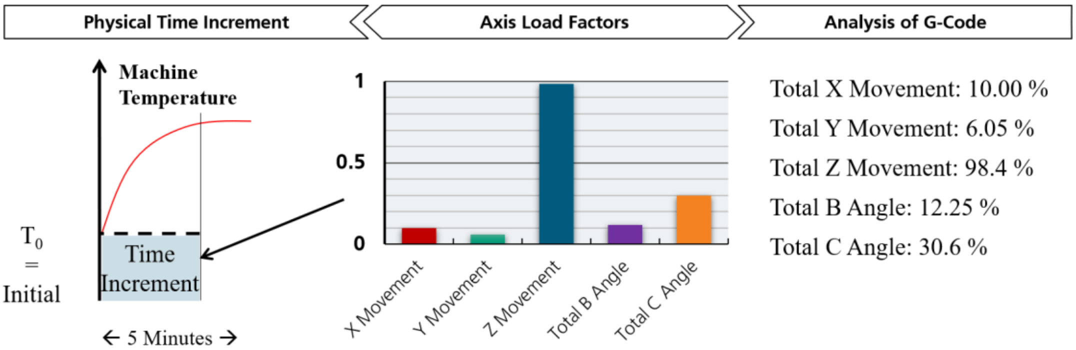

Fig. 3. Determination of physical boundary conditions using histograms (5 min load steps)

With the help of the histogram generator, a histogram for a time period is generated based on the trace data from the machine. A visualization, showing the frequency of movement of each machine assembly as percentage factors enables the easy identification and assignment of BCs corresponding to the associated guide rail segments (Fig. 3). The transfer of the new BCs for the current time increment to the FE model is fully automated so that the simulation can be started immediately. The BCs and the histogram percentage factors are managed in a central Excel spreadsheet and linked to the parameter set for BCs in the FE model. This table is linked via a macro control and the "histogram generator" in a programming environment.

The length of the time increment, within which the BCs are considered constant, depends on various factors and significantly influences the precision of the resulting compensation model. The most important factors include the load case structure, the rate of ambient temperature changes and the thermal inertia of the machine. Compared to mechanical effects, thermal processes are relatively slow, so that time intervals of several minutes can be considered reasonable. For large machines and a stable indoor environment, the time increment can also be longer. In the case of rapidly changing operating conditions, large time increments can lead to a smoothing of the simulation data and thus cause deviations between simulated and actual thermal machine state. Too small time increments, on the other hand, may lead to very long computation times. As a result of the simulation, temperature and displacement data are generated in ANSYS and exported in *.TXT files and stored centrally, whereupon the generation of new CDs can be initiated in the next step, as outlined in Chapter 3.

3. AUTOMATIC GENERATION OF NEW CHARACTERISTIC DIAGRAMS

With the help of a new software, characteristic diagrams can be created from temperature and displacement data [27]. This application reads the previously generated text files containing temperatures and displacements of the load case and writes the computed CD to an XML-File. The CDs can be loaded into a compensation routine (app) in the control system, as described in Chapter 4. The CD and the load cases on which they are based are stored in a database so that the monitoring application can access them later. The mathematical background for calculating the CDs is documented in detail in [27]. A single CD always applies to only one direction (X, Y or Z) and a specific machine pose, so that at least three CDs are required for compensation in three degrees of freedom (DOF). Currently, only the three translational directions (X, Y, Z) are being compensated with the CD based error model. Error predictions for the angular error components (5-axis) are already being computed from the simulation data. However, since it is difficult to determine exactly which portion of the measured relative TCP displacement comes from the machine tool column and which portion from the table, the rotational components were omitted. As soon as reliable data for the table deformation is available for the validation of the rotational error predictions, these values will be added to the compensation routine. This task is part of current research. In the first step, CDs have to be calculated in relation to the basic load cases (= single axis runs with max. axis speed). In the second step, CDs are calculated from a set of simultaneous axis motions. In the third and final step, the CDs have to be generated automatically using the histogram generator and the analysis of the current load case in the machine using the monitoring application as a demonstration scenario.

An example of an unknown and practice-oriented load case is shown schematically in Fig. 4, where an overall period of 16 hours is considered. During this period, different axis movements and different spindle speeds are divided into eight blocks, with each block representing a different, fictitious workpiece.

During this reference measurement (measurement data of the displacement, see Fig. 4 right), which took place in an air-conditioned environment at a constant ambient temperature of 20°C, temperatures and the corresponding TCP displacements (thermal error) were recorded. From the evaluation of the machine data for the underlying load case, the BCs for the FE model were determined and the load case simulated. After the FE simulation, in which the resulting temperatures and displacements were generated and stored, the CDs can be calculated from them using the CD generator in the next step.

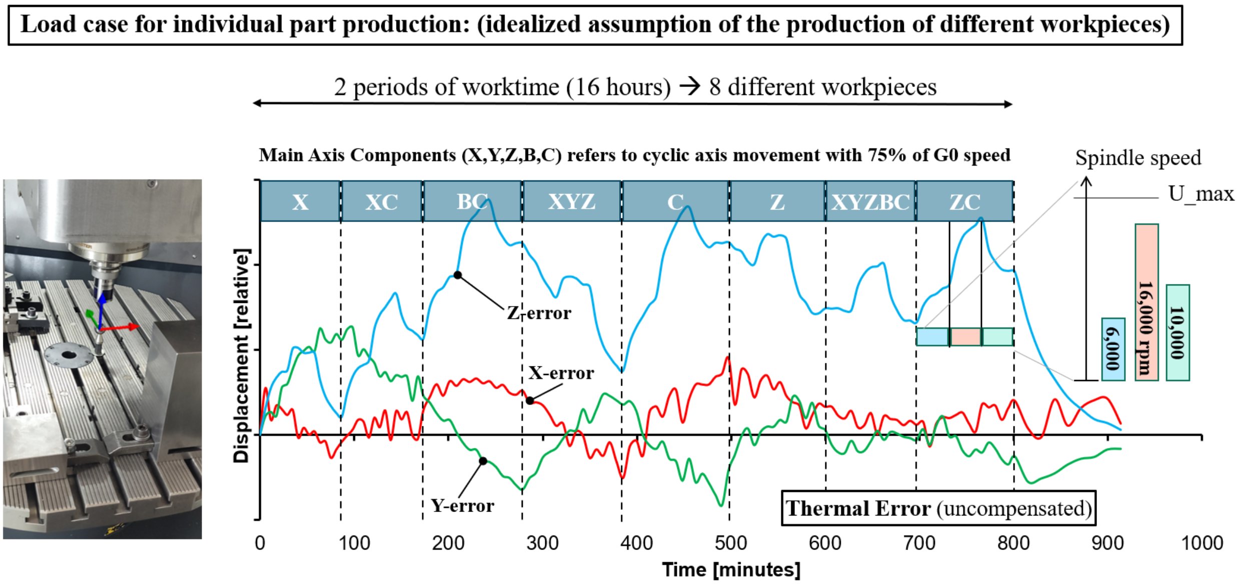

Fig. 4. Example of an unknown and continuous load case (schematic diagram)

The tool for generating and saving CDs runs on the demonstrator PC, where the result data calculated from the FE simulation is stored. Temperature and displacement data are required and imported as .TXT files from the FE calculation in order to generate the CDs. The relative displacements are calculated as the difference between the deformations of the tool center point and a reference FE node from the machine table. To realize a compensation in three degrees of freedom, at least one FE node on the tool side and one on the table side are required for the evaluation. For a five-axis compensation, the spindle tilt and the table tilt must also be taken into account. To do so, at least three FE nodes on the table surface and two on the *Z*-slide in different *Z*-positions need to be evaluated.

The CDs are time-independent, as they only correlate the temperature profiles at the selected temperature locations to the associated geometric displacements (Fig. 5).

	*.TXT Temperatures									*.TXT Displacements		
[s]	[°C]								[s]	[µm]		
time	*T1*	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*	*time*	*X*	*Y*	*Z*
0	20.5	20	20	20	20	20	20	20	0	0	0	0
60	20.5	21	20	20.1	20	20.1	20	20.2	60	3	2	5
120	20.5	21.5	20	20.2	20	20.2	20	20.3	**120**	7	3	11
...	...	...	...	...	...	...	...	...	...	...	...	...
1020	20.5	29	20	21.7	20	20.4	20	21.6	1020	65	18	90
	Yes	Yes	No	Yes	No	No	No	Yes		Yes	No	No
				(Active Input)							(Active Input)	

Training data set reference value

Fig. 5. Example of dataset for the calculation of CDs for the *X*-error

The figure shows an example of the text files generated from the simulation for CD training. In this example, the DMU 80 evo has eight integrated temperature sensors, which are available as inputs for the algorithm for CD generation. In practical use, the CD calculation proved to be better and more efficient if there is a high correlation between the measured temperature values and the displacement. This is tested before calculation by comparing the differences between minimum and maximum for each set of temperature sensor values in addition to testing the covariance. If a difference falls below a threshold value of 0.5 K, a significant correlation for the load regime under investigation can be ruled out and the measuring point is not used as an input variable for the CD (Active Input = No, in Fig. 5). This allows an adaptive selection of suitable CD inputs. In the next step, the temperature interval limits (minimum and maximum temperature for the respective input) are defined and the interval range is discretized. The discretization determines the number of grid support points in the CD, which are used for the interpolation. A high number of grid points can provide a more accurate prediction, but the memory size and calculation effort of the CD increase significantly, and also the risk of overfitting increases. Overfitting leads to the CD approximating the data too closely at the cost of less precise general predictions away from the known data points / thermal machine states. There should always be a good balance between the CD's grid fineness (degrees of freedom of the model) and the amount and distribution of the training data.

At the end, the CD calculation software delivers a set of CDs in .XML format, which can be used via an application in the NC. How many CDs are used, depends on the architecture of the CD based compensation. The simplest version requires only three CDs (one for *X*-, *Y*- and *Z*-error), each with up to 13 input values (8 temperature sensors and 5 axis coordinates).

4. IMPLEMENTATION OF THE HYBRID COMPENSATION AND INTEGRATION INTO THE NUMERIC CONTROL

The methodology presented here aims to integrate all of the components required to implement the hybrid compensation. The following Fig. 5 provides an overview of the hybrid compensation with the main processes and components. This includes the following modules, as described in the previous chapters:

- *Thermo-elastic finite element model* (FE model): is based on a simplified CAD geometry of the entire machine (w/o housing) and the subsequent meshing with 3D solid elements. The FE model computes and exports *.TXT-files of temperatures and displacements.
- *Structure model:* is based on the FE model after using MOR techniques, such as Krylov method, and calculates temperature fields from machine data. It is real-time capable due to the employed ROMs.
- *Histogram generator* (BC generator): generates thermal BCs by analysing G-Code or trace data from the machine for a given time period. The BCs are derived from histogram factors between 0 and 1, which reference percentages of the maximum axis speeds.
- *CD generator*: calculates CDs in .XML-file format for each direction (*X*, *Y*, *Z*) from *.TXT-files containing simulated temperatures and TCP displacements.
- *Monitoring application:* runs in the background and compares the temperature field calculated by the structure model for the current machine state with the temperature

signature to which the active CDs were trained. If the deviations are too large, a suitable set of CDs is searched in the database or a new simulation and CD computation is initiated.

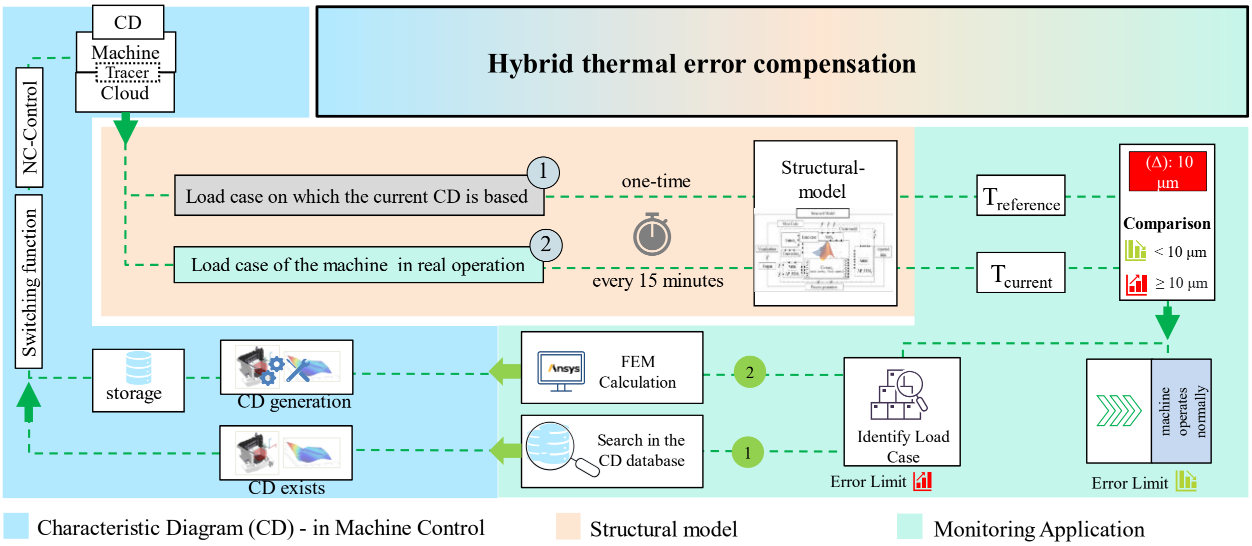

Fig. 5. Overview of the implementation architecture of the hybrid methodology

Integration takes place in a central software environment in which all components have access to the required interfaces. This enables the hybrid compensation to be implemented and offers the user the best possible performance. With the help of modern and secure IT structures, data management can take place centrally in a network or in a cloud and the required applications can be outsourced to external and powerful computers if necessary. This ensures that the machine control system is not overloaded by both regular background processes and the computing operations required for the error compensation. This requires the machine's programmable logic controller (PLC) to be connected to a computer via a suitable interface. In this example of the DMU 80 evo, the machine control is connected to a PC with a Windows environment. This PC can be accessed via a standard network access (TCP/IP) and the network data link is used to exchange the machine data with the structure model as well as to load new CDs from the database.

The second integration object required is a computer on which all processes for the thermal displacement calculation can run. The FE model and the module for calculating the CDs consume the most resources. An FEM environment is required to calculate the new load cases, in this example ANSYS Mechanical. The calculation time and memory requirements depend heavily on both model size and number of load steps. Additional interfaces for Python and MATLAB are required for the automated generation of BCs based on histograms.

A series of sequential processes, which operate interdependent on each other, constitute the hybrid thermal compensation concept. The monitoring application primarily focuses on decision-making within the context of hybrid thermal compensation while validating the CD pre-defined in the machine. A complete cycle of hybrid thermal compensation starts and ends at the machine as follows: machine → tracing → structure model → monitoring application → CD creation if necessary → CD upload to machine control → machine. During the machine operation, the load case is continuously recorded in the form of trace data and communicated to the structure model via a cloud interface. The structure model computes temperatures (T) at eight sensors distributed across the DMU 80 evo. Initially, the structure model calculates temperatures at the sensor positions based on the current pre-defined CD's load case – these temperatures are saved as Treference and will later act as a reference for the comparison to new temperature fields, see Fig. 5. Subsequently, temperatures based on the machine's current load case are calculated every 15 minutes, facilitating continuous real-time monitoring of the machine's actual state. This temperature set is termed Tactual.

At the comparison block (Treference-Tactual), an exemplary threshold of 0.5 K is set for triggering updates. While this limit is not reached, the machine and structure model continue their operations for further checks without any CD change. The CD is considered valid for the current machine state. The acceptable temperature difference for the validity of the CD depends on factors such as permissible displacements and can be user-defined. If the limits are too narrow, the CD may have to be changed more frequently, which would be uneconomical (high calculation effort). The user has to decide from a practical point of view.

The load case is identified via a newly developed histogram generator for every run of the structure model and in case the error threshold is reached, this load case definition is conveyed further to the two sequential steps: Firstly (1), a search commences in the CD database to locate the corresponding CD for the identified load case. If found, this CD is utilized in the NC-Control through a switching function that exchanges the active CD. If none is found, then the second step (2) is initiated: Once the necessity for a new CD is detected and confirmed by the monitoring application, a thermo-elastic FE simulation is executed. As outlined in Chapter 3, this simulation calculates temperatures at various sensors and corresponding deformations at the TCP. After this pre-processing step, a console program written in C# generates the CDs from the selected combinations of temperature inputs for all axis directions (X, Y, Z). The resulting CDs from this generation step are saved in an XML file format and stored in the CD database. These CDs can then be used directly in the PLC or NC for position correction by a running application ("thermal error compensation software"). Alternatively, the CDs can be used for the separate estimation of the thermal error for a set of individual workspace positions with subsequent position-dependent geometric interpolation in the NC/PLC. The interactions and interfaces of the FE simulator, CD generator, CD machine integration as well as the structure model and the monitoring application are presented in Fig. 6.

As soon as the first suitable CDs for a machine are ready, the compensation can be implemented on the machine control system, where multiple integration options are available. First, the method for offsetting the NC position values needs to be selected, as this determines how the compensation is implemented. Depending on the controller type, this step can be carried out using an existing temperature compensation feature from the control manufacturer. Spatial compensation of temperature influences, as intended by CD based compensation, is usually not directly possible with existing interfaces and must first be implemented.

The compensation of ambient temperature changes could be included in the hybrid approach by treating it as just another thermal load. A reference sensor in the machine (T8), which correlates with the ambient temperature, can be used for this purpose. This sensor also only correlates with the ambient temperature and is not influenced by the machine load. The current thermal error compensation model combines different models for internal and external thermal loads in order to reduce the complexity of the submodels and to minimize the required training data, see [31]. Therefore, the machine load specific model updates developed in this paper only affect the internal portion of the overall compensation model, which is independent from the ambient temperature.

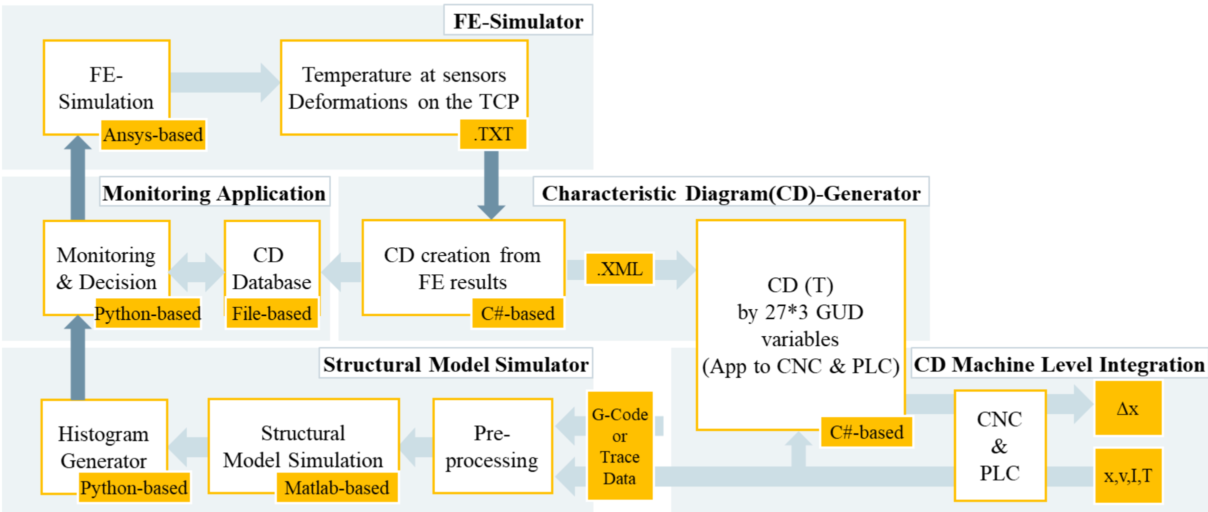

Fig. 6. Implementation of the hybrid methodology into the numeric control

In the separation of thermal and geometric interpolation used here, the compensation generally consists of two cycles. The first cycle calculates the temperature-dependent displacement values for all interpolation points in the workspace on the basis of the actual temperature sensor values. As thermal influences are relatively slow, this cycle is executed with a moderate cycle time, here every 5 s. The second cycle interpolates the spatial displacement from the workspace support points for the current commanded TCP position. This interpolated value is the offset needed for thermal error compensation. The influencing variable in this second cycle is the current machine position, so this control loop must be processed as quickly as possible, typically every 2 to 4 ms.

The specific implementation is performed using the example of the SINUMERIK 840Dsl machine tool control system from Siemens AG. Several options are available for integrating the control loop: The most elegant way is integration as a compile cycle. The SINUMERIK provides an open interface for the integration of custom functions directly in the core of the NC control, which can, however, only be used by licensed developers or by Siemens. Furthermore, additional license fees are required per machine to execute these software functions. A second option, which also enables the calculation in the interpolation cycle, is to implement the control loop using synchronized actions. Synchronized actions are short calculation functions that can be executed in parallel to the NC program. However, a large number of synchronized actions are required to implement the complete control loop, which may lead to increased utilization of the NC controller. A third option is to integrate the control loop into the PLC, which is responsible for sequence control and signal processing. The PLC typically operates in the lower two-digit millisecond range and is therefore significantly slower. As the location-dependent thermal error only changes significantly with larger movements, the slightly longer PLC cycle times during milling do not lead to additional losses in accuracy.

In the online compensation used here, the temperature sensors are read by the PLC every 5 s and transmitted to the operating and visualization PC. The workspace support point displacements are calculated from this temperature vector and transferred back to the PLC. The PLC saves the updated compensation tables and a synchronized action interpolates the position-dependent displacements and applies the resulting offsets.

Once the machine-level integration is completed, a validation procedure is performed involving the integration of all software components (including histogram and CD generators and simulation models) on a single PC connected to the machine control. Next, experiments are simulated on virtual CNC connected to this PC. This enables the monitoring and regular testing of the validity of the CDs and ensures that the generation and switching functions are working according correctly.

5. CONCLUSION

This contribution evaluates and describes the concept and practical implementation of a hybrid thermal error compensation method on a machine tool. The methodology requires the machine tool to have the corresponding control interfaces and a suitable set of temperature sensors as inputs for the compensation. The CD based compensation requires simulative generated training data, that represents the real machine tool's thermo-elastic behaviour. The error predictions from the CDs provide position offsets for the NC path during the machining process. A structure model monitors the validity of the currently running CDs in the background by analysing the machine state in thermal real-time. A predefined threshold for the CD validity can be used to check whether the active CD represents the current machine load case in a correct way. If the threshold value is exceeded, an automated process is initiated to search for a suitable CD in a database. If the search is unsuccessful, the machine operator receives a warning that there is not yet a suitable CD in the database. The operator can then initiate the semi-automated generation of a new CD from FE simulations, for which the necessary BCs are generated automatically using the histogram-generator.

For a machine tool with a Siemens 840Dsl control and a connected Windows computer with network access, the hybrid compensation methodology was implemented. The structure model was implemented from a parametrized thermo-elastic FE model [10]. The algorithm for CD generation was already developed and extensively validated prior to the investigations described here [27].

In order to transfer the concept to other machine types, the new and complete modelling and parametrization of the FE model and the MOR for the structure model are necessary. A limited re-parametrization is also necessary if the machine condition changes significantly over a long period of time (e.g., due to wear). There are further hurdles if a different type of control is used. As the solution described has so far only been tested on a Siemens control, it remains to be validated for other control types. In this context, further research is necessary to ensure complete transferability. Further work will also be necessary to demonstrate the use of the hybrid compensation for actual cutting operations.

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