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Modeling the thermal machine tool error during cooling lubricant usage

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Abstract

The thermo-elastic machine tool error, which is one of the main error sources in a machine tool, can be modeled and corrected using the machine control. In the past, the models to do so have been parametrized using precise measurement equipment like lasertracers. However, these lasertracers cannot be used to measure the thermo-elastic error during cooling lubricant usage, which is necessary for most industrial applications. Therefore, this paper presents a method on how to measure the thermo-elastic machine behavior using Integral Deformation Sensors to compute the tool center point displacement during coolant usage based on a white box modeling approach. These computed displacements are then used to parametrize a correction model that uses low order delays elements.

Keywords: thermal deformation; thermo-elastic behavior; machine tools; Tool Center Point; correction

1. Introduction

In terms of productivity and sustainability, a high reject rate during production causes an enormous loss. It is known, that a large share of the workpiece errors are caused by thermally induced Tool Center Point (TCP) deviations [1]. The usage of cooling lubricant has a significant impact on the thermo-elastic machine behavior [2] [3]. Since its usage is very common in the industry, a better understanding and correction of the thermally induced deviations caused by cooling lubricant is an absolute necessity to enable a more reliable production [4]. However, most of the thermo-elastic error models rely on sensitive measurement equipment for parametrization, which cannot be used when cooling lubricant is distributed in the machine. Therefore, this paper presents a measurement method to parametrize a thermo-elastic error model during coolant usage with Integral Deformation Sensors (IDS).

2. State of research

2.1. Cooling lubricant in machine tools

Cooling lubricant has various tasks within a machine tool [5]. Its most important tasks are the cooling of the cutting area and the reduction of friction by lubrication. Cooling the cutting area is necessary to reduce thermo-elastic deformation of the tool and the workpiece, as well as reducing wear on the tool. However, during the process, the cooling lubricant is distributed in the whole working volume of the machine tool, cooling all the components [3]. Current research on the matter focuses on the description of the impact of cutting fluid on the thermo-elastic TCP displacement [6]. By comparing the machine behavior during coolant usage and in dry conditions, Mayr et al. found that coolant usage significantly impacts the TCP displacement [4]. Pavlicek et al. compared the usage of standard cooling lubricant to the usage of CO_2 in a machine tool and found that the usage of CO_2 reduced the thermo-elastic deformation of the axis by more than 60 % in one of the axis [7]. Hernandez-Becerro et al. investigated the influence of the cutting fluid supply in the working volume on the TCP displacement. The results show, that different cool-

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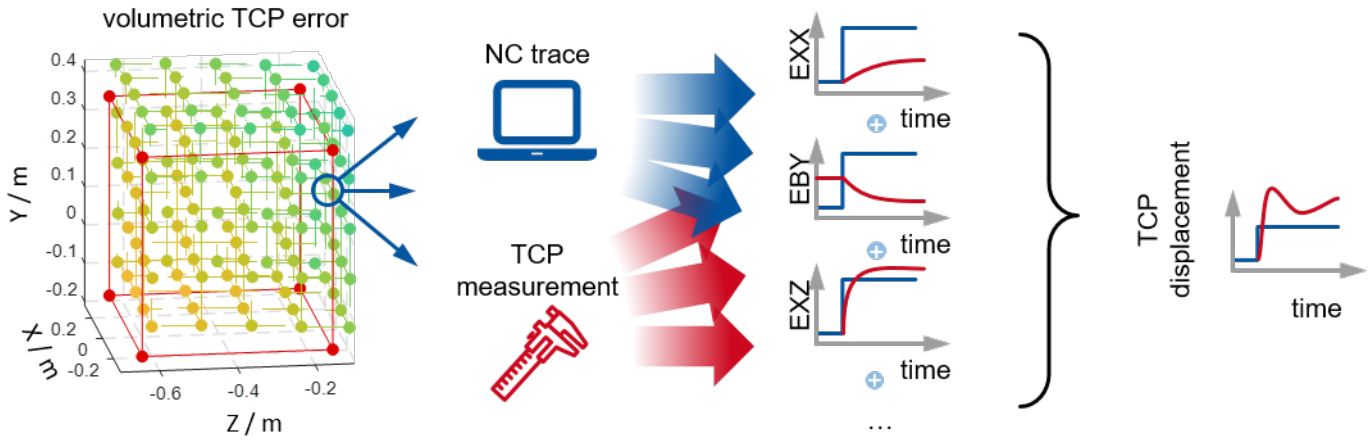

Fig. 1. Modeling the TCP error using first order delay elements.

ing lubricant outlets have a varying influence on the TCP displacement [8].

2.2. Modeling the thermo-elastic machine error

There are multiple approaches in the literature focussing on modeling the thermo-elastic error for correction using the machine control. The approaches used here can be clustered into white box [9], gray box [10] and black box models [11] [12] [13], with each having its own advantages and disadvantages in specific use cases. All of these models have in common, that they need a measurement of the TCP displacement for parametrization. This paper however will focus on a gray box model using first order delay elements to model the TCP, which is described extensively by Wennemer [14]. Therefore, other approaches of modeling the thermo-elastic machine tool error will not be discussed further in this paper. A sketch of the model using first order delay elements is shown in Fig. 1.

The displacement of the TCP in the working volume due to thermal changes in the machine tool is very complex and cannot be described by low order delay elements. However, when considering the total TCP error as a superposition of axis error components [15], Wennemer made the observation, that these error components follow low order delay element characteristics [14] [16]. The machine is put under load and the effect on the volumetric TCP error is measured to parametrize the delay element. For modeling axis movement, a single axis is moved back and forth continuously using the maximum speed of 25 m/min. The resulting thermo-elastic TCP displacement is measured in intervals of 10 minutes volumetrically using the lasertracers and transformed into single axis errors [17]. The measurement setup for the parametrization is shown in Fig 2. Four lasertracer mounted to the bottom of the machine table measure the TCP position using multilateration [18]. Fig. 3 shows the result of the EXX error at position X: 0 mm, Y: 350 mm and Z: 600 mm. The K-T-factors parametrizing the element are obtained using a best fit algorithm. The trial is repeated for each machine load (axis movement, spindle speed, machine start up and change in ambient temperature) evaluating all single axis errors each time. The investigations show that only a few selected single axes errors are needed for the parametrization. Some axis errors did not show a response to the machine load. Fig. 3 shows which single axes errors show a significant thermal behavior and are parametrized. Variables marked with "n" in the figure take the axis speed as input, and variables marked with "T" take the corresponding linear scale temperature as an input. These latter variables are not modeled using a delay element, but rather a linear element. [14]

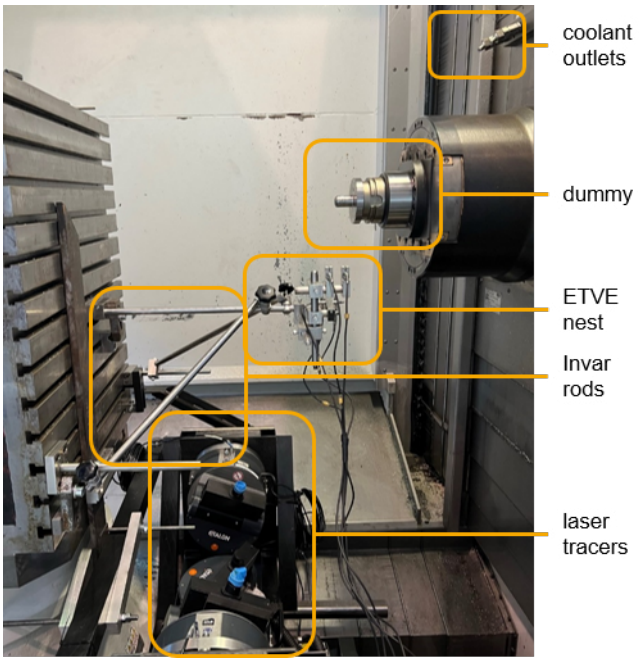

Fig. 2. Experimental setup for the measurement of the TCP displacement during coolant usage.

By superposing all elements, the TCP error can be modeled for complex machining operations and used to correct

the error using the control. Wennermer was able to reduce the error of a machine tool from 42.3 ± 6.6 µm to 12.5 ± 3.8 µm using this method [14]. This model is taken as a basis in the presented paper. While the upside of using the lasertracers is their accuracy, the downside is their susceptibility regarding environmental conditions. Coolant is widely used in the machining industry, which means that modeling the TCP error during coolant usage is essential for a successful application of the model. However, it is not possible to parametrize the machine behavior of the coolant using the lasertracers, since the coolant interrupts the laser beam, thus disturbing the measurement. Therefore, an alternative measurement procedure is needed to parametrize machine tool behavior during coolant use. IDS are well suited for this application [19] since the sensor position allows for a process parallel, uninterrupted displacement measurement during coolant use. The measurement principle of the IDS is explained in the following chapter.

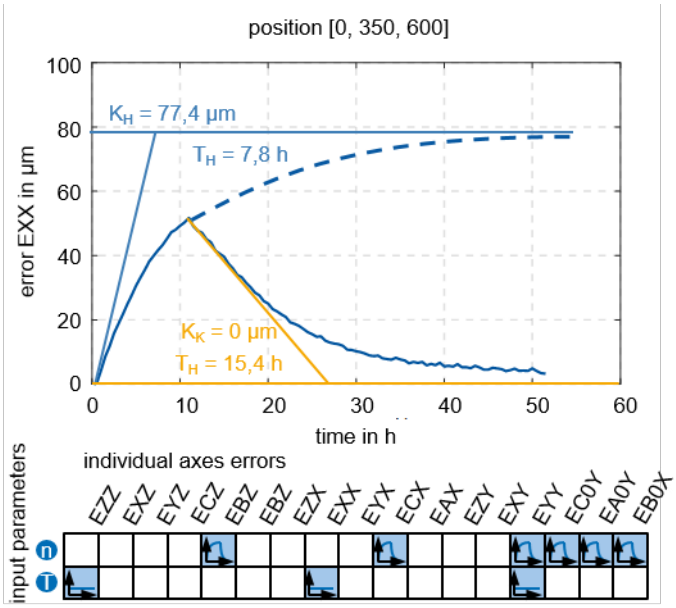

Fig. 3. PT element parametrization and parametrized elements for the investigated machine.

2.3. Integral Deformation Sensors

To enhance the thermal stability of machine tools, Brecher et al. developed a method which is based on IDS as described in [20] and [21]. To measure the thermally induced length change of the machine structure components, a thermally stable CFRP rod is used as reference.

As depicted in Fig. 4, one end of the rod is held by a fixed bearing, which allows the measurement of the underlying machine structure deformation at the loose bearings side. Next to the measurement surface at the end of the rod, a displacement sensor is placed, which is connected to the machine structure by a rigid connection. The idea of this measurement is described in [22].

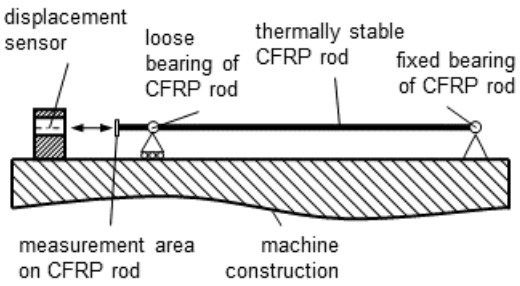

Fig. 4. Schematic design of the IDS

To model the TCP displacement using the IDS sensors, multiple sensors are mounted to the machine structure components, which contribute the most to the TCP displacement. The expected deformation can be derived from thermo-elastic simulations or based on experience gained while using the machine. The TCP displacement is modeled based on the IDS sensor measurement using various mechanical theories. Components that are expected to hold significant amounts of shear stresses are modeled using Timoshenko beam theory. Components without shear stresses are modeled using Euler-Bernoulli beam theory. The frontal part of the machine bed for example is modeled using the Euler-Bernoulli beam theory, firstly because of the high ratio between its length and height/width, but also because shear stress is not expected. For elements which can not be modeled as a beam, the approaches discussed in [23] are used.

For the presented work, nine sensors are mounted onto the machine structure. Three IDS are placed onto the moving frame of the X axis, three onto the frontal part of the machine bed, and three more are attached to the rear part of the machine bed. The sensor placement for this specific use case is also discussed in [23], by comparing it to a mathematically optimized placement, which shows equally good results.

3. Comparison of models

The model using low order delay elements introduced by Wennemer has proven to accurately model the machine tool behavior without cooling lubricant usage. However, a delay element modeling the behavior with cooling lubricant usage is not yet parametrized. The aim of this paper is to parametrize such an element. However, this is not possible using the lasertracers since the coolant lubricant can damage the tracers (compare sec. 2.2). Therefore, the IDS model will be used for parametrization. Before the parametrization using the IDS model, the IDS model is compared to the results of the low order delay element model in the following without coolant lubricant usage to validate the procedure. An individual uncertainty is assigned to each model represented by an area of the corresponding model color in the figures, i.e. the yellow area surrounding the yellow graph to show the IDS model results and uncertainty. In the presented work, a four axes horizontal machining center with axes length between 700 and 850 mm is investigated. For this machining

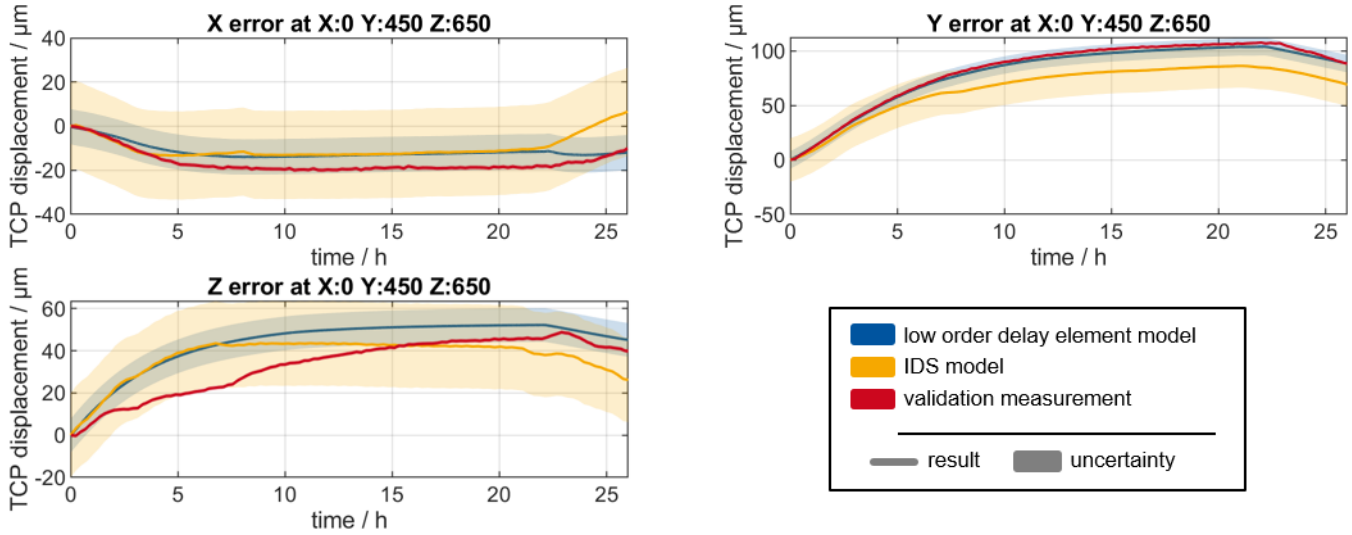

Fig. 5. Modeling the thermo-elastic TCP error of a simple load case using a low order delay element model and the IDS model

center, the accuracy of the low order delay element model is investigated extensively. It results to an accuracy of ±8 µm containing the uncertainties of modeling the TCP displacement resulting from axes movement. [14] In previous investigations, the uncertainty for the IDS model was quantified as less than 10 µm [23]. However, this investigation was based on sensors that were mounted to the machine structure using screws on each bearing. For this specific machine, it was not possible for three of 18 bearings to be mounted by screws; glue was used instead. The influence of this change was investigated, showing that a measurement using glued sensor bearings increases by 70 - 80 % in comparison to the screw mounted sensor measurements. To consider this influence, the uncertainty of the computed TCP displacement was considered higher.A worst-case estimation to 20 µm is used.

To detect any change in accuracy through the substitution of lasertracer measurements by the modeled TCP displacement using the IDS model, the already parametrized low order delay element model from Wennemer [14] is compared to the IDS model for a known load scenario. In this case, the machine tool is put under an internal thermal load by rapid axis movement of the X axis between the positions −400 mm and +400 mm and a set axis speed of 30 mm/s for a duration of 22 h. Due to change in travel direction at the reversal points, the average axis speed results to 22.7 mm/s. After those 22 h, the machine is stopped, which results in cooling of the machine components. The application of load and the cool down is interrupted repeatedly to conduct the displacement measurement. This load case is chosen since the low order delay element model has been parametrized by Wennemer for a similar load case using the TCP displacement measured by lasertracers. The TCP displacement is then modeled using the low order delay element model presented by Wennemer as well as the IDS model described in section 2.3. Additionally, the TCP error is measured using an environmental temperature variation error test (ETVE test) according to ISO 230-3 [17]. For the ETVE test, five digital dial gauges measure the TCP displacement at the machine pose X: 0 mm, Y: 450 mm, Z: 650 mm as reference for both models. One sensor measures the axial displacement and the other sensors the radial displacement, as shown in Fig 2.

The validation measurement using the ETVE test [17] shows a typical delay element behavior in all directions. The maximum elevation of the delay elements is -20 µm in X direction, 105 µm in Y direction and 47 µm in Z direction. The low order delay element model computes a very similar result. For the conducted experiment, the validation measurement using the ETVE test is within the uncertainty boundary of both models for the X and Y error. The Z error is only within the uncertainty boundary of the IDS model between hours 2 to 15 and within the boundary of both models for the rest of the experiment. In conclusion, both models are able to display the TCP displacement almost entirely correct. This means, that both models are capable of computing the TCP displacement in real time.

The trial was repeated using a more complex thermal load scenario. For this scenario, the machine is put under a randomly varying internal load by varying the X axis speed over time. The result of this measurement is shown in Fig. 6. For this load scenario, a similar result can be observed. The ETVE measurement is within the uncertainty boundaries of both models for the X axis error, while it surpasses the boundary for the IDS model within the last quarter of the experiment for the Y error and the boundary of the delay element model during the first half of the experiment for the Z error. However, those results show that the IDS model results can be used to parametrize the delay element model without loosing a significant amount of accuracy.

4. Parametrization for coolant usage

The results from the previous section show, that it is possible to compute the TCP displacement using the IDS in the

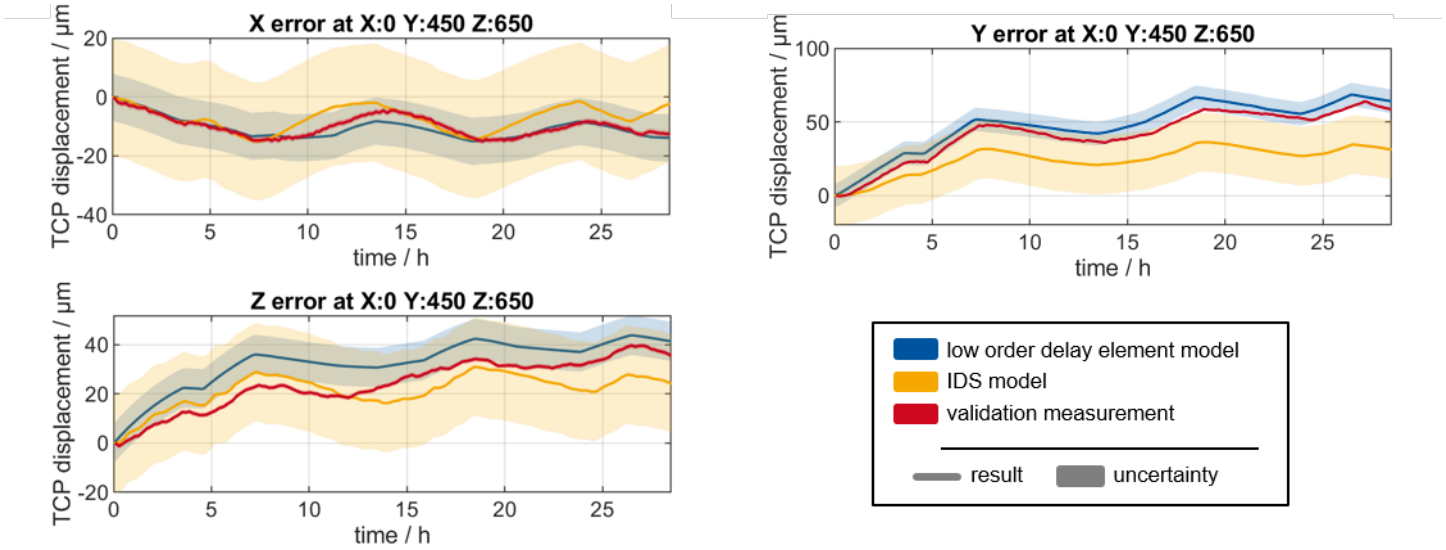

Fig. 6. Modeling the thermo-elastic TCP error of a varying load using a low order delay element model and the IDS model

same way the lasertracers are used. Using the IDS enables a computation of the TCP error for machining operations, where a measurement using the lasertracers is not possible. In this section, the low order delay element model first introduced by Brecher [10] is extended by a low order delay element to model the thermo-elastic TCP error resulting from cooling lubricant usage.

The influence of cooling lubricant on the TCP error is dependent on the TCP position, since some of the coolant outlets are attached to the spindle and vary with its position (compare Fig. 2). It is assumed, that K and T factors for the low order delay elements for a cooling fluid element change continuously depending on the machine pose (compare Fig. 3). The continuity of the factors would allow for an interpolation of the factors between parametrized positions. The goal of the investigation in this section is to check, whether this interpolation is feasible.

For this, cooling lubricant is activated for 12 h and subsequently turned off. The IDS measurement is used to compute the TCP displacement in the working volume. The experiment is conducted at three different machine poses, which are positioned in a straight line. The outlying two of those experiments are used for parametrization and the center experiment, which is positioned exactly between the other two, is used for validation. For parametrization, the low order delay elements are fitted. Subsequently, the K and T factors of these two outer positions are interpolated to build a low order delay element for the center position. The delay element is then used to model the TCP displacement for the third experiment. Here, the computation made based on the IDS-measurement is used as validation. Fig. 7 shows the modeled TCP displacement using the extended low order delay element model, as well as the TCP displacement using the IDS model.

The computed TCP displacement shows a typical low order delay element behavior during cooling lubricant usage. The low order delay element model is able to predict the TCP displacement within its uncertainty of 8 µm considering an uncertainty of 20 µm of the IDS model computation with especially high accuracy in Y and Z direction. In X direction, the model shows a slight deviation to the validation at the maximum displacement. In summary, the result shows, that it is feasible to model the TCP error in the presented manner.

5. Summary and outlook

In the presented work, the TCP displacement was modeled using two existing models: a low order delay element model and an IDS based model. Using a validation measurement with dial gauges with high accuracy, it is shown, that both models are able to measure the TCP displacement within the given accuracy of each model.

After this validation of the two models, it is shown that it is possible to parametrize a low order delay element for the TCP displacement due to cooling lubricant usage and that the delay elements can be interpolated for machine poses not previously parametrized. This was validated using one machine pose while utilizing two machine poses for parametrization. For industrial applications, it is necessary, to investigate the feasibility of this modeling procedure for the complete working volume. Future works should therefore aim at efficiently building a grid to enable correction in the whole working volume. Critical positions that are necessary for parametrization should be identified for a stable model of the TCP error coming.

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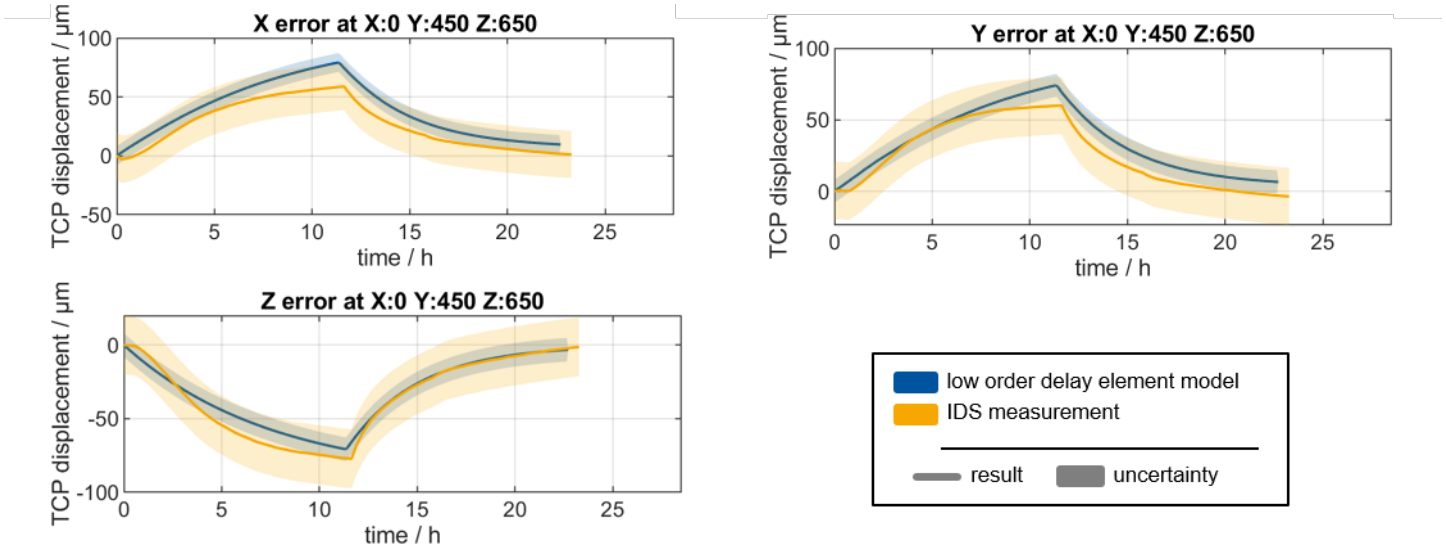

Fig. 7. Modeling the thermo-elastic TCP error during KSS usage. Validation of the result using the IDS model.

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