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# Ambient temperature effect on the volumetric error of a large milling machine

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## Abstract

Thermal errors represent one of the main error sources regarding to the volumetric accuracy of a machine tool. These errors can be induced by internal localized heat sources or by variations in the room temperature which affect to the whole volumetric performance. In this work a large milling machine model is presented and the effect of the ambient temperature in volumetric error is analysed. Model Order Reduction software allows to perform multiple evaluation at different machine position and temperature states, allowing full volumetric evaluation of the machine performance.

Machine tool, thermal error, ambient temperature, volumetric error, model reduction

## 1. Introduction

Thermal errors are amongst the main error sources regarding to the volumetric accuracy of a machine tool, along with the kinematic and dynamic errors [1]. These variations, which cause relative displacement between the Tool Center Point (TCP) and the workpiece, can be induced by internal heat sources, e.g. rotating spindle, linear axis drives or cooling system, or by variations in the room temperature.

Thermal errors caused by internal heat sources can be abrupt and less predictable, compared to those caused by the environment, but they are usually localized. Therefore, monitoring critical temperature variations and measuring its effects can be an easier task. Environmental effects usually lead to smooth temperature changes on the machine tool, but they affect the whole volumetric performance.

As in smaller machines environmental errors can be easier to characterize [2] measuring these effects in big machines represents a major challenge. Firstly, room temperature variations may be significant along the workshop volume, requiring a complete mapping of the machine temperature, with multiple probes in appropriate locations. Secondly, several points should be measured in the machine volume to properly characterize thermal error behaviour dependency with axes position, which involves difficulties in the implementation and accuracy of such measurements in large volumes. And last, implementing a compensation model that predicts thermal error is not straightforward, as several temperature inputs should be considered. These temperatures will usually show high correlation between them and lower signal-to-noise ratio to the displacements measured, compared to internal heat source effects.

Taking these aspects into account, characterization tests would require from several days to a week, involving specific measuring instrumentation [3], making this task time and cost ineffective. Hence, modelling and simulation play a major role on characterizing machines and efficient developing of compensation models.

Simulations using Finite Element models represent the most common approach, using them in different steps of the characterization and compensation process [4]. However, calculations usually require a considerable amount of time, especially in large machine models where the number of elements can be significant. Moreover, obtaining results in different axes position of the machine can be a difficult task in regular FEM programs, where the moving contacts between the axes are not prepared for such simulations.

Lately, Model Order Reduction (MOR) techniques has been used to reduce simulation time and analyse thermal error effects. Furthermore, FEM based reduction and simulation programs has been developed, that allow mechanical and thermal MOR and simulations in different machine positions using special interfaces between moving parts [5].

In this work environmental thermal effects will be analysed on a large moving-column milling machine model. MORe, a model order reduction software, will be used to simulate ambient temperature effects in the thermal error at different points of the machine volume. In section 2 the machine and several modelling aspects are presented. In section 3 some simulation results will be showed and analysed. Section 4 contains the main conclusions out of this work.

## 2. Modelling and methodology

In this section the machine model and the simulation procedure are presented.

### *2.1. Machine model*

The machine modelled is a moving-column type milling machine with three linear axes. The moving parts of the machine, i.e. the column (X), the console (Z) and the ram (Y), along with the machine head, are supported by a bedplate (b2) that is fixed to the ground. The workpiece lays over another bedplate (b1), which is also fixed to the ground. Both bedplates have no other contact or bound between them. A schematic view of the machine is represented in figure 1 and table 1 summarizes main machine characteristics.

**Table 1** machine specifications. Kinematic chain represented according to ISO 841 and ISO 10791-6 (t: tool; b: bed; w: workpiece).

| Machine tool | X (mm) | Y (mm) | Z (mm) |
|---|---|---|---|
| Working volume | 0-4000 | 0-1200 | 0-1500 |
| Kinematic chain | t – Y – Z – X – b2 – b1 - w | | |

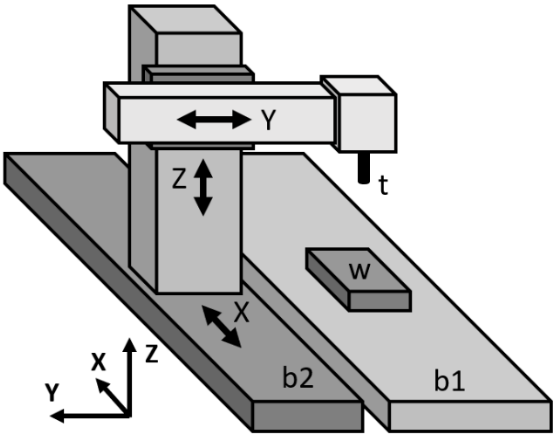

**Figure 1.** Schematic view of the machine structure.

All linear axes are position-controlled by the machine control using linear glass scales.

### *2.2. Modelling*

A Finite Element model has been developed, including all the structural elements explained in section 2.1. A workpiece has not been included as these simulations aimed a more generalized analysis of the whole machine volume, nor has the tool, as its length may vary from case to case. The toolholder origin has been used as the reference point for the TCP instead. The metrics of the model are listed in table 2.

Most parts of the machine are made of structural steel, whose structural properties are available in most material libraries. The joints between moving parts, i.e. guidelines, carriages, ball screws and bearings has been modelled according to the mechanical and thermal properties provided by the manufacturers. Linear glass scale expansion effect has been included to consider its influence in the position control loop.

To simulate transient thermal effects in different axis positions thermal transient simulation is performed in the first place, varying ambient temperature. This way, complete temperature map of the machine is obtained for several time steps ($T_1$, $T_2$… $T_n$). Then, measuring points are defined in different axis positions ($\mathbf{X_1}$, $\mathbf{X_2}$ … $\mathbf{X_m}$) and the thermomechanical model is used to evaluate all of them with the temperature field in each time step. Figure xx shows a diagram of the simulation process.

**Table 2** FE Model metrics

| FE Model DOF | Mechanic | Thermal |
|---|---|---|
| Full | ~ 1 700 000 | ~ 560 000 |
| Reduced | 1720 | 490 |

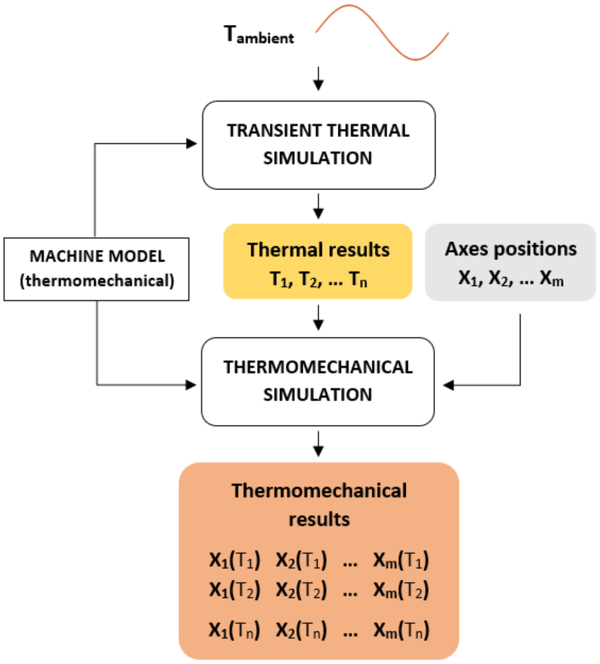

**Figure 2.** Diagram of the simulation process

## 3. Simulation and results

A 24h ambient temperature variations has been simulated, measuring the relative displacement between the TCP and the working bed (b1) at different axis positions. For that purpose, all external surfaces of the machine parts have been exposed to convection heat exchange with the air. The air temperature varies in a sinusoidal way, with ±5ºC variation, in a similar way workshop temperature may change due to day/night 24h cycle. Initial state has been set to 20ºC for all machine parts and transient thermal simulation has been perform.

Measured positions were generated by a 9x4x4 regular grid in all the machine volume, resulting in 144 points for each time step. These points have been evaluated every 30 minutes to obtain the thermal error of the machine through 24h. Table 3 summarizes simulation specifications.

**Table 3** Ambient thermal simulation specifications

| Ambient thermal simulation | |
|---|---|
| Ambient temperature | $T_{amb} = A \cdot \sin(2\pi f \cdot t)$ ; A = 5ºC ; f = 1/24h |
| Axes position grid | 9x4x4 (**XxYxZ**) ; 144 total positions |
| Sampling period | 30 min ; 49 total instants |

Figure 3 shows the thermal error evolution for 24 hours in two different TCP positions. Deviations in X direction are plotted along with the ambient temperature. As it can be seen, X position affects to the thermal error in the machine volume. Both points show different behaviour in magnitude and phase through 24 h. As the first point (located at the middle of X, 2000mm) shows typical delayed behaviour with respect to the ambient temperature, the second one shows several effect, mainly related with the edge effect of both beds.

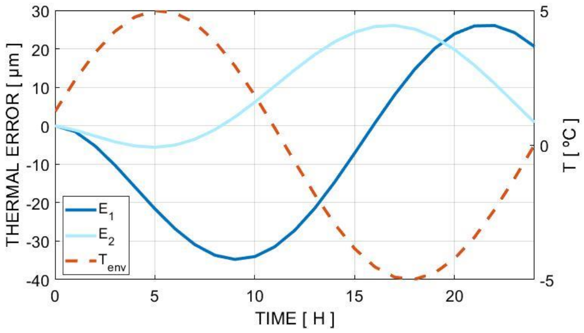

**Figure 3.** Thermal error through 24h for 2 measured points. E1 (dark blue) at X = 2000mm and E2 (light blue) at X = 3500mm, at same Y and Z positions. Thermal input is plotted in red.

Figures 4 shows the position-dependence behaviour of the thermal error, where the X direction error is shown for the XY plane at Z = 50mm position. 2 different time steps are shown to appreciate the evolution in time.

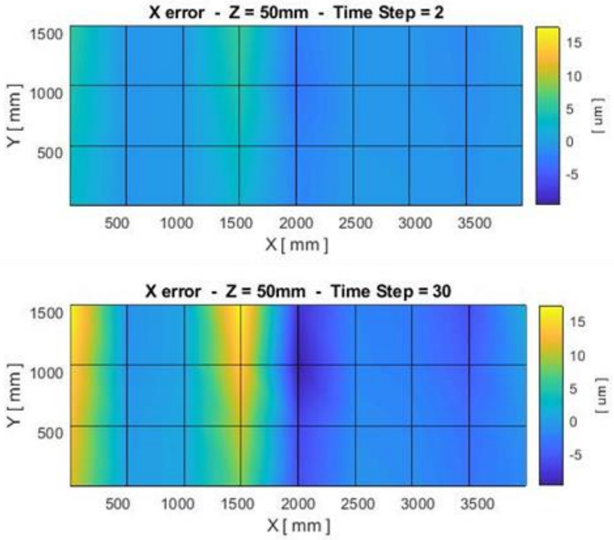

**Figure 4.** Thermal error through 24h for 2 measured points. E1 (dark blue) at X = 2000mm and E2 (light blue) at X = 3500mm, at same Y and Z positions. Thermal input is plotted in red.

## 4. Conclusions

- Complete thermal behaviour of a large machine tool has been simulated, allowing to evaluate the thermal error at any point of the machine volume. Such a volumetric evaluation has only been possible due to Model Reduction techniques applied with the mentioned software.

- Position dependency has been observed in the evolution of the thermal error. Along with the evolution over time, the study of such effects has allowed to understand different behaviour of the machine parts.

- In opposition to typical compensation strategies, this methodology approaches thermal errors as time and position dependent and will allow to develop compensation models that consider both aspects.

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