euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
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The MIIM method for the environmental thermal error study of large machine tools: A real case study

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Abstract

Large machine tools are extremely sensitive to environmental temperature variation as the heat flows through the machine structure and induces linear and non-linear structural deformation. It results in machine tool error when it is operated in long term regimes such as machining processes that take longer than 3÷4 hours. Its experimental testing can take from days to weeks of machine downtime and the associated cost in production. Additionally, the volumetric measurement of environmental thermal errors in large machine tools presents some challenges that encounter the limits of production metrology. All these limitations lead to a few researchers orienting their investigation to the study of the effect of the ambient temperature variation on large machine tool accuracy.

In this scenario, this research works presents a prototype of how to use the so-called machine tool integrated inverse multilateration method for the environmental thermal error characterization of large machine tools and aims to correlate the obtained results with an a priori and offline finite element analysis study. To get there, a real case study is presented where a Leica AT402™ laser tracker is integrated within a Zayer Arion G™ machine tool and Spatial Analyzer™ software is employed to automate the complete measurement process and realize the inverse multilateration scheme. Before the real measurement, the machine tool has been modelled in the finite element analysis software and an a priori Monte-Carlo simulation has been run to preview the measurement scenario configuration and to understand the potential uncertainty budget.

Finally, three batches of measurements have been performed during different days and under uncontrolled environmental conditions. The obtained measurement uncertainty is low enough to characterize the machine tool thermal drift and deviation results correlate with the a priori finite element analysis study of the machine tool.

Keywords: Machine tool, Thermal error, Integrated multilateration, integrated laser tracker

1. Introduction

Thermal distortions are the main limitation for accurate large machine tools (MT). According to Mayr et al. [1], up to 75% of the overall geometrical errors of a machined workpiece can be induced by the effects of temperatures. The combination of the varying ambient temperature in uncontrolled manufacturing environments with the heat generation during the metal cutting process results in thermally induced tool centre point (TCP) displacements in MTs [2].

As explained by Mian et al. [3] MTs derive from varying environmental conditions such as the day and night or seasonal transitions during which large temperature swings can occur. Thus, thermal gradients cause heat to flow through the MT structure and result in linear and non-linear structural deformations which induce MT error when it is operated in long term regimes.

As stated by Gross et al. [4], while many of the studies in this field focus on internal heat source study, few researchers have oriented their investigation to study the effect of the ambient temperature variations on the MT accuracy. Thus, they propose the use of a climate simulation chamber subjecting an MT to different constant temperatures while applying a sequential multilateration scheme with a LaserTracer™ to map the thermo-elastic errors on the TCP. They conclude that squareness and linear positioning errors are dominantly affected by ambient temperature variation while straightness and rotational errors are less sensitive to temperature effects.

Many solutions exist to measure the displacement of MTs at TCP but very few approaches can respond to the challenges of measuring the effect of thermal effects in large MTs [1]. In this way, Egaña et al.[5] presented a measurement approach, the so-called Machine Tool Integrated Inverse Multilateration (MIIM), for the environmental thermal study of large MTs where the main challenges are fulfilled by integrating an absolute distance measurement device within an MT spindle to realize an inverse multilateration scheme.

Compared to the International Organization for Standardization (ISO) ISO 230:3-2020 [6] standard tests that suggest local displacement measurements between the TCP and the workpiece, the MIIM approach suggests a volumetric error mapping procedure that shall be used to complete those tests performed at the environmental temperature variation error (ETVE) tests.

Following the MIIM simulation-based research presented by Egaña et al. in [5], this article presents the experimental realization of the MIIM method for the thermal characterization of a large MT by integrating a Leica AT402™ laser tracker within a Zayer Arion G™ MT spindle. The measurement automation sequence is realized by Spatial Analyzer™ (SA) software and allows running repetitive measurements with no-human intervention during the complete measurement acquisition process. In total, three batches of measurements have been performed during different days and under uncontrolled environmental conditions. Each batch is comprised of 20 repetitions.

2. The MIIM method

The MIIM approach developed by Mutilba et al. [7], is an integrated multilateration verification procedure where an absolute interferometer is directly attached to the MT spindle as explained in Figure 1. Thus, the MT depicts a volumetric point grid where the measurement device is sequentially brought by the MT and from which the distance measurement to every fiducial point fixed on the MT is realized.

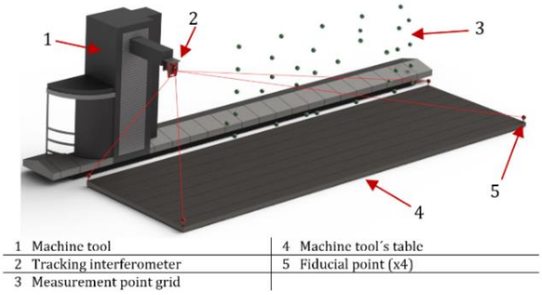

Figure 1 Integrated multilateration approach [7].

Compared to the typical multilateration approach, where tracking capacity is needed on the tracking interferometer side to track the reflector position in space, this integrated approach suggests a unique MT working volume travelling where the pointing to every fiducial point occurs in sequence and automatically. Thus, the spatial relationship between fiducial points and the volumetric point grid shall be established beforehand. Under this measurement strategy, the integrable technology shall need to re-establish the distance datum which currently is done through the absolute distance measurement (ADM) technology. Thus, pure incremental distance measurement interferometry (IFM), such as the previously mentioned LaserTracer™ or IFM-based laser trackers, is discarded since it cannot accomplish the MIIM measurement procedure without having to return the reflector to the datum position to reset the measurement system. Moreover, the MIIM approach demands a wireless instrument for either power or data transfer with the laptop and CNC for long run tests.

Considering that a unique MT working volume travelling is needed to realize the multilateration scheme, the total-time consumption during the data acquisition process is reduced within an hour. It avoids the MT thermal drift to a high extent and therefore the measurement uncertainty obtained with the MIIM approach improves the obtained with the traditional method.

3. The machine tool under research

The MT of interest is a Zayer Arion G™ portal-type machine tool which is a five axes multitasking machine. The considered MT working volume for the experimental test is X 500 mm, Y 2.000 mm and Z 500 mm. The MT is divided into two main structures, either the tool side (columns, cross beam, saddle or Y-slide and ram) or the workpiece side (bed, X-slide, and rotary table). Both structures are independent and are connected to the floor.

Figure 2 shows a) the finite element analysis (FEA) MT model and b) the MT on the shop floor at TEKNIKER premises.

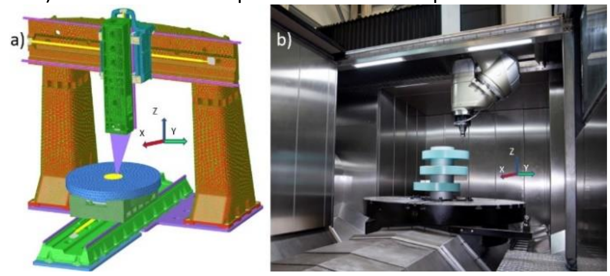

Figure 2 The Zayer Arion G™ MT a) FEA model and b) the MT at Tekniker facilities.

The machine is thermally monitored using different temperature sensors, some of them are placed internally, close to those mechanical elements where heat is generated such as the spindle or the feed drive motors, and the others are placed externally to monitor the ambient and the substructures. Every temperature signal is timestamped to unequivocally combine the information for the posterior MT TCP displacement/temperature correlation analysis.

The MT under research has been simulated by FEA to understand how the MT behaves under different thermal conditions. As addressed by Mian et al. [3], the FEA method shall be an efficient approach to efficiently estimate the MT distortions but as they remark in their work, an MT is rarely at thermal equilibrium and therefore establishing the initial conditions for the FEA simulation of environmental change presents a significant challenge as it adversely affects the comparison of the FEA and experimental results.

In this case, the MT symmetrical design allows good behaviour at different stable temperatures which results in almost a linear MT structural deformation according to the ambient temperature variation. Figure 3 depicts how the angular and perpendicularity errors between the columns and cross beam are low at three different stable temperature conditions a) 23 ºC, b) 20 ºC and c) 17 ºC.

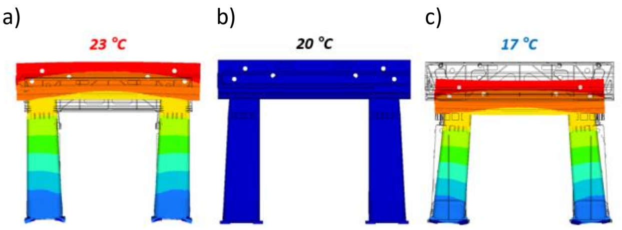

Figure 3 The MT columns and crossbeam deformation at three different stable temperatures.

In other words, Figure 3 a) and c) cases mean a) a steady-state condition in which the MT is at a higher ambient temperature than when it was assembled and c) the opposite where the MT is at a steady-state condition at lower ambient temperature.

Similar to the FEA initial condition establishment, it is also hard to acknowledge the MT geometry right after the MT assembly process because there are some uncertainty contributors such as the ambient temperature, components geometry or the assembly process itself that affect the initial MT geometry. However, from this initial MT condition, the MT TCP (columns and crosshead) structural deformation due to temperature variation behaves as follows: (Figure 2-a shows the column and crossbeam structure and the MT reference system)

X-direction: The MT TCP tends to move away from the crossbeam. This movements´ sensibility to the MT Y and Z positions is low.

Y-direction: Due to symmetry, the deformation is cero on the centre and becomes higher as far as the TCP is close to the Y-axis ends. The deformation decreases a little bit when the ram is extended.

Z-direction: The ram suffers a linear deformation proportional to the temperature variation. This error increases when it is extended since there is an additional free length to elongate. The MT table also suffers a linear deformation which means that when the ambient temperature increases the distance between the workpiece (on the table) and the TCP decreases.

4. Experimental test

Experimental research of how the available Zayer Arion G™ large MT geometry changes according to the environmental temperature variation at shop floor conditions is performed at Tekniker premises. In total, three batches of MIIM measurements have been performed during different days and under uncontrolled environmental conditions. Each batch is comprised of 20 repetitions and takes 14 hours to be realized. The experimental tests described in this article were made in the middle of May and the last week of July 2021.

4.1 Performed tests

After an initial calibration process where the MT reference system, the integrated instrument and the fiducial points reference systems are aligned [7] in common, a CNC ISO G-code [8] is repeatedly run at the MT to realize the data acquisition process. The MT movement and the MIIM data acquisition processes are synchronized via transmission control protocol/internet protocol (TCP/IP), so the measurement procedure is run in a fully automated measurement sequence with no-human intervention.

Figure 4 shows the MIIM prototype at the MT. Note that four wide-angle reflectors are located on the MT table (X-axis) and a Leica AT402™ laser tracker is integrated within the MT TCP (YZ-axis) to realize the inverse multilateration approach.

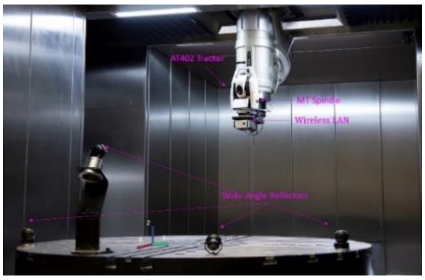

Figure 4. MIIM test configuration on the Zayer Arion G™ MT.

The point cloud is defined by seventy-six points distributed in XY, YZ and ZX planes that intersect between them. This configuration eases the posterior inverse kinematic (IK) exercise to solve the MT kinematic parameters that enable a potential volumetric correction. Figure 5 shows the measurement configuration.

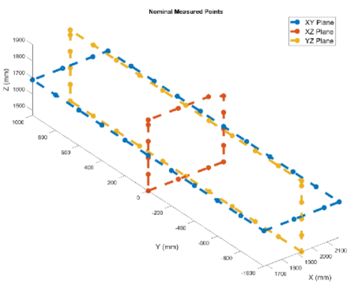

Figure 5. MIIM test configuration on the Zayer Arion G MT.

Every movement during the MIIM execution is made very slowly and it takes three seconds at each measurement point to stop the MT and realize the distance measurement. Thus, no thermal distortions are introduced to the MT by internal heating sources during the MIIM materialization. The unique heat source is therefore the ambient temperature variation. In this way, the refrigerators of the main spindle and the rotary table are disconnected several hours before the tests to assure that they do not introduce any heat source or sink depending on the ambient temperature of the day.

5. Results

Every MIIM repetition takes 40 minutes which compared to the MT FEA results conclude that the measurement procedure is fast enough to avoid structure thermal distortion during the data acquisition process. This conclusion is obtained from the machine FEA model response to a unitary step increment of temperature. Approximating the machine thermal behaviour to a first-order system, all the substructures have a time constant (63.2% of the step value) higher than 40 minutes. Figure 6 shows the time response of each of the tool-side substructures, showing how the columns have the fastest response with a constant time near 40 min and a higher time-response for the rest of the substructures.

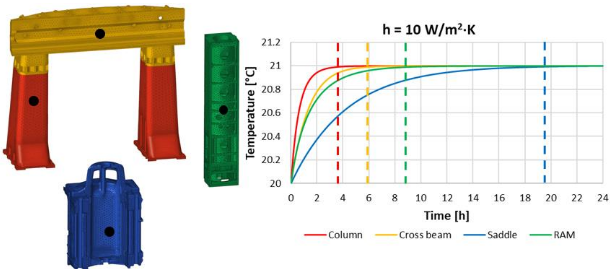

Figure 6. Tool-side structures response to a unitary step increment of temperature.

The ambient temperature stability during the test campaign was remarkably high with less than 1ºC variation within any of the three batches of MIIM measurements. However, the absolute temperature difference was considerable with more than 4.5ºC between the measurement of May and those performed at the end of July. Figure 7 shows the MT temperature measured on the cross beam during the data acquisition processes.

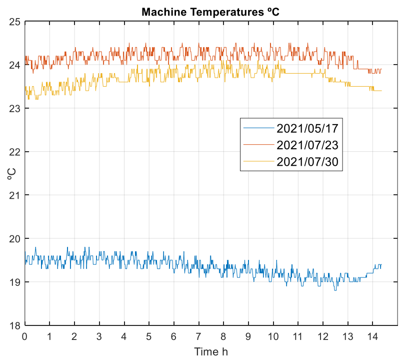

Figure 7. Temperature measured on the cross beam during MIIM tests.

The MIIM results show repeatability better than 10 µm in X and Y axes while it is within 15 µm in Z axes. The reason why it is worse in the vertical direction is due to a unique fiducial point being fixed out of the XY plane as depicted in Figure 4. A second fiducial point being fixed out of the plane shall improve the Z-axis measurement uncertainty to the obtained in X and Y directions.

Table 1 shows the average standard deviation value on the X, Y and Z axis per measurement day. It shall be highlighted that results correlate with the measurement instrument employed, an ADM-based laser tracker with a spatial displacement measurement expanded uncertainty U (k=2) = 10 µm+ 0.4 µm/m [9].

Table 1 Average standard deviation of the MIIM test campaign. (µm)

	17-may	23-jul	30-jul
X-axis	8,1	5,3	4,5
Y-axis	5,2	4,7	4,3
Z-axis	11,8	12,5	11,6

Figure 8 depicts the absolute deviation at each of the measured points for the 20 MIIM repetitions for the test performed on 23/07/2021. It demonstrates how the MIIM repeatability is negligible compared to the MT absolute geometric error which is within ± 0.1 mm at the moment when the test campaign is executed.

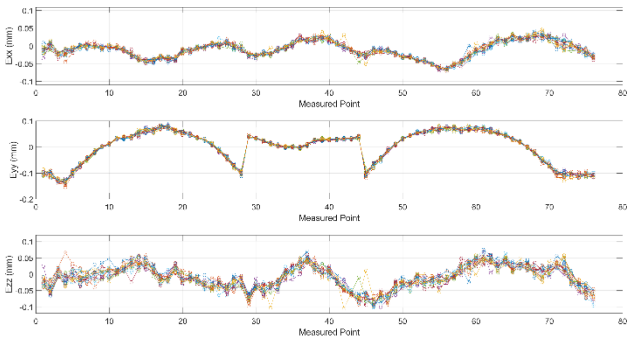

Figure 8. Errors Measured at each point. a) E_X b) E_Y c) E_Z

Focusing on the Y-axis measurements performed at the end of July when the temperature is 4.5ºC higher (on average), it demonstrates that deviation increases as temperature rises. Figure 9 shows the observed effect in Y-direction during the three batches of MIIM measurements compared to the FEA result in the bottom picture as the MT travels the working volume. The correlation between the measured and FEA is realized.

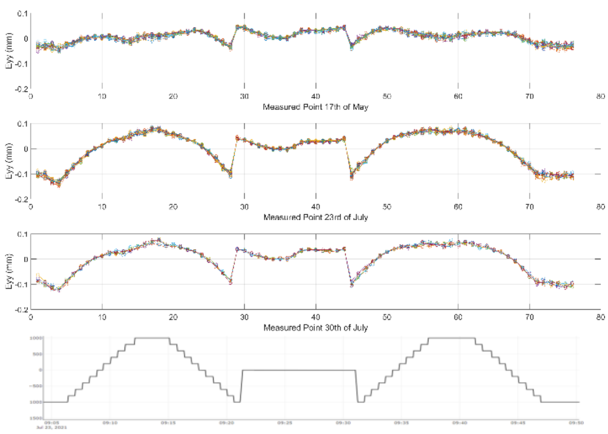

Figure 9. Error in Y-direction measurement by the three batches of MIIM measurements and compared to the FEA results.

6. Conclusions

This article presents the MIIM prototype for the thermal drift measurement of a Zayer Arion G™ large machine tool. A total of three batches of measurements are realized with a Leica AT402™ mounted on the MT spindle. Thus, it is demonstrated the feasibility of the MIIM approach to enable an automated, fast, accurate and volumetric method for the characterisation of large MTs with a minimum influence of the thermal errors.

The experiments and the FEA analysis show that the measurement procedure (40 min) is fast enough to avoid structure thermal distortion during the data acquisition process allowing dozens of error maps creation in a single day.

Measurement uncertainty results show that measurement repeatability is better than 10 µm in X and Y axes while it is within 15 µm in Z axes for those measurements performed at stable temperature situation (within 1ºC in 14 hours). Comparing the repeatability of the MIIM approach with the absolute MT deviation, it is demonstrated that MIIM repeatability becomes negligible.

Considering the MT absolute deviation, the MIIM experimental test shows how the MT deviation increases as ambient temperature variation rises, showing a correlation between those measured deviations and the simulated FEA results. It is shown in detail for the MT Y-axis.

As future research lines, additional experiments shall be realized at different MT configurations to scale the MIIM approach to any large machine tool configuration and develop a robust measurement solution for the thermal error study of large MTs that is compliant with requirements defined by Mayr et al. in [1]. The real integration exercise on the Zayer Arion G™ MT highlights the need to develop a new concept of distance measurement CNC instrument to allow materializing the MIIM method by reducing the cost and improving the distance measurement uncertainty.

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