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Efficient estimation by FEA of machine tool distortion due to environmental temperature perturbations

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ABSTRACT

Machine tools are susceptible to exogenous influences, which mainly derive from varying environmental conditions such as the day and night or seasonal transitions during which large temperature swings can occur. Thermal gradients cause heat to flow through the machine structure and results in non-linear structural deformation whether the machine is in operation or in a static mode. These environmentally stimulated deformations combine with the effects of any internally generated heat and can result in significant error increase if a machine tool is operated for long term regimes. In most engineering industries, environmental testing is often avoided due to the associated extensive machine downtime required to map empirically the thermal relationship and the associated cost to production. This paper presents a novel offline thermal error modelling methodology using finite element analysis (FEA) which significantly reduces the machine downtime required to establish the thermal response. It also describes the strategies required to calibrate the model using efficient on-machine measurement strategies. The technique is to create an FEA model of the machine followed by the application of the proposed methodology in which initial thermal states of the real machine and the simulated machine model are matched. An added benefit is that the method determines the minimum experimental testing time required on a machine; production management is then fully informed of the cost-to-production of establishing this important accuracy parameter. The most significant contribution of this work is presented in a typical case study; thermal model calibration is reduced from a fortnight to a few hours. The validation work has been carried out over a period of over a year to establish robustness to overall seasonal changes and the distinctly different daily changes at varying times of year. Samples of this data are presented that show that the FEA-based method correlated well with the experimental results resulting in the residual errors of less than 12 μm.

1. Introduction

The shop floor environment where a CNC machine is located can be of paramount importance for accuracy of manufacturing. Temperature controlled environments require high capital investments and running costs, which are undesirable and sometimes impractical. In environments where the temperature is not controlled, the changing day and night cyclic transitions and myriad other sources [1,2] can cause ambient temperatures to vary significantly both in magnitude and rate-of-change. These temporal fluctuations can cause spatial thermal gradients in a machine tool; the heat flow through the structure over time causes non-linear thermal deformations. Several research projects have been conducted to identify, predict and compensate the overall effect of the thermal distribution in a machine tool but with main emphasis on solving the effect of internally generated heat, particularly from the main spindle and during the machining processes. For example, Hao [3] used a genetic algorithm-based back propagation neural network (GA-BPN) method using 16 thermistors placed at the spindle, headstock, axis leadscrew and on the bed of a turning machine to compensate dynamic and highly nonlinear thermal error. Only one ambient temperature sensor was used which may not be sufficient to capture detailed environmental behaviour around the machine vicinity. The author reported the thermal error compensation improvement of 63%. Further reduction could be possible if detailed external environmental temperature swings were considered. Similarly, research from Yang et al. [4] tested an INDEX-G200 turning centre and used MRA technique to predict its thermal accuracy. The analysis result showed that the thermal error range for radius direction on that machine was approximately 18 μm, higher than expected. 14 thermal sensors were installed in groups and only one ambient sensor was used. While modelling, six temperature groups with variables were constructed and the model was assumed to be a linear function for the environmental temperature

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rise. The predicted thermal error between the spindle and the cutter revealed a residual error of 5 μm from a maximum error of approximately 18 μm for a test length of 4 h. Modelling time was not mentioned. Tseng and Chen [5] proposed a thermal error prediction model derived from the neural-fuzzy theory. IC-type temperature sensors and a Renishaw MP4 probe system were used to measure the temperature changes and thermal deformations respectively. Sensors were attached to the spindle motor, spindle sleeve side with one sensor measuring environmental variations. The prediction model improved the machining accuracy from 80 μm to 3 μm. The prediction model was further compared with MRA revealing accuracy improvements of ±10 μm to ±3 μm. However, the model training times and machine downtime are accountable issues with this research. One of the regression techniques known as orthogonal regression technique was employed by Du et al. [6]. This technique was applied to more than 100 turning centres of the same type and specifications. It was found that the technique was able to reduce the cutting diameter thermal error from 35 μm to 12 μm. The technique was stated as robust due to its year round repeatable improvement in accuracy. The accuracy is expected to increase if long term shop floor environmental temperatures fluctuations were considered.

Many researchers drew attention towards the environmental thermal drifts in machine tools which arise from a variety of sources while they emphasised the machine downtime required for detailed environmental testing as well as analysing the modelling methods and modelling time. Rakuff and Beaudet [7] drew attention to the importance and effect of the environmental temperature variation error (ETVE) while conducting a cutting test of 24 h on a diamond turning machine. The research suggested the provision of temperature controlled enclosures for the machine to avoid external thermal drifts to improve the accuracy of the process control. Fletcher et al. [8] provided useful information about cyclic environmental fluctuations and drifts with 50% reduction in error over a 65 h test, but drew attention to the detrimental amount of machine downtime for the thermal characterisation tests. Longstaff et al. [2] showed several tests conducted for the thermal error measurements produced by the environmental fluctuations combined with long term machining. The authors also highlighted some unexpected, rapid fluctuations of the environment with its effect on the accuracy of the machine. They also highlighted the machine downtime issues related with the measurements. Jedrzejewski et al. [9] discusses the complexities involved with improving the design of a machine tool when considerations of reducing thermal error are in focus. A highly accurate thermal model of the machine is presented and consideration of various parameters contributing to the thermal behaviour. For example, the design criteria considered the effects of environmental variations for 2.5 days, thermal effects arose due to the presence of guarding and bearing sets of high speed spindles. Quartz straight edges were modelled for environmental effect after mounting on the machine centre support beam. It was found that the straight edge fixed on the left side produced the lowest error of the other three locations tested. The information related to the FEA such as the modelling time was not clear and the operating conditions were not clearly stated. A concern shown by Bringmann and Knapp [10] about the effect of thermal drift while showing how increasing the number of measurement points (from 4 to 60) can lead to reduced uncertainties and higher accuracy for identified location errors of the rotary *C*-axis. The author reported that the further increase in the measurement points only leads to limited improvements as it can lead to extra time for measurement which increases the uncertainty of the thermal effect arising from environmental or ambient temperature changes until the measurement is complete.

It is apparent from the discussion that a great emphasis has been given to control the thermal effects mainly arising due to internal heating. As a result, most existing commercial error compensation systems deal with axis growth and spindle heating while neglecting ambient effects on the remainder of the structure. It is also apparent that a significant amount of machine downtime is associated with environmental testing particularly when the dominant cycles are daily or even weekly; Longstaff et al. [2] reported a significant issue for machines that experience a weekend shutdown. In most cases environmental testing to establish a relationship between temperature and response is avoided due to the cost to production associated with machine downtime. However, this omission can be critical when striving for the best possible accuracy of the machine tool. The problem is exacerbated since the scope of conditions during which test data can be acquired is very limited compared to true variation over facility operations and natural seasons.

This paper presents a novel offline environmental thermal error modelling method based on FEA that significantly reduces the machine downtime required for effective thermal characterisation. The proposed modelling method was tested and successfully validated on a production machine tool over a year period and found to be very robust (in this paper, samples of data measured during two seasons are presented). The validation confirmed the potential of this method to reduce the machine downtime normally required for the environmental testing from a fortnight to a few hours. The paper also highlights the effects of seasonal environmental temperature changes in a machine tool and the presence of vertical temperature gradients within a shop floor environment. The paper also describes on-machine measurement methods to acquire the required data efficiently using strategically placed temperature sensors during any convenient maintenance schedule period.

2. Proposed method

In general, environmental temperature changes are not as rapid as those from internally generated sources such as spindles. Additionally, there can be several different structural responses which require different metrology equipment to measure that cannot be used concurrently. Therefore, environmental testing normally takes from two days to several weeks to acquire sufficient data to establish the various relationships between varying temperature profiles and the response of the machine. To overcome the machine downtime issue, a novel modelling methodology based on a two-stage FEA is proposed in this paper where a Computer Aided Drawing (CAD) model of the machine is created in the FEA software (in this study Abaqus 6.7-1/Standard was used) [11]. This is followed by a determination of the initial thermal state for the FEA model, a key method developed in this research, which will establish a close match of the real initial thermal condition of the machine before conducting environmental simulations.

2.1. FEA modelling

A machine tool is, in practice, rarely at thermal equilibrium. Consequently, establishing the initial conditions for the FEA simulation of environmental change presents a significant problem as it adversely affects the comparison of the FEA and experimental results. To represent the realistic initial thermal state of the machine structure is a challenging task if the real temperature gradients are to be measured and applied to the model. Experimentally, the application of the individual temperature sensors at locations within the machine structural loop is laborious and prone to uncertainty in locating sensitive areas. In contrast to thermal error from running the machine where the heat sources are easy to identify for application of the sensors, environmental changes affect the whole structure. However, even if this is achieved, modelling the initial thermal state of the machine in the FEA software

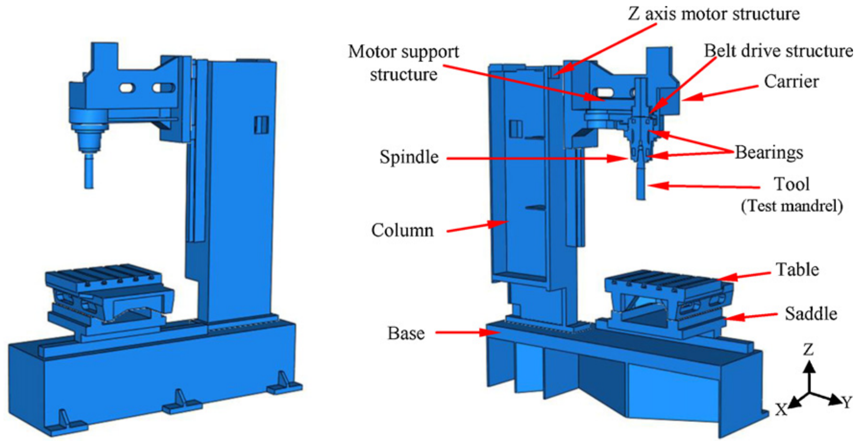

Fig. 1. Generated CAD model of the machine assembly with *Z* axis head moved up compared to [1] in essence to present a newer model corresponding to new test conditions.

remains challenging. Sectioning the modelled parts in the software and applying individual temperatures to them may represent the initial thermal state but it is a strenuous task and may cause incorrect temperature gradients due to section joints. This problem is solved by the proposed novel method which determines the initial thermal state for the machine model and also provides an estimate of the minimum time required for an environmental test on a machine (Section 2.3).

2.1.1. Machine model

A model of the machine is required. For the case study machine, a model described by the authors [1] with respect to internally generated heat was used to estimate the long-term environmental response. The machine was a precision 3-axis Vertical Machining Centre (VMC) with accuracy up to 3 μm; tested by manufacturing a NAS-979 component [12]. Simplified models of the machine were used to carry out offline simulations of the environmental behaviour of the machine, details of which are shown in Fig. 1.

The model was meshed using tetrahedral, hexahedron and hexahedron dominated (hexahedron/wedge) elements where applicable using Abaqus default meshing technique which revealed the total of 49,919 elements and 20,418 nodes. Fig. 2 shows the meshed assembly of the machine. All simulations are performed as transient thermal simulations where changing data from the temperatures sensors is applied in the software using the tabular amplitude technique.

2.2. Estimation of initial thermal state of the machine

Generally, prior to the start of any test, the machine elements exhibit variations in temperature due to the existence of temporal and spatial thermal gradients. In particular, vertical temperature gradients have been found to be significant [2,13]. As a result, it is unfeasible to accurately set initial temperatures of the components in the FEA software to match reality. A new technique of a two-stage simulation in Abaqus has been devised and applied to solve this problem. The first stage simulation in effect will estimate the time span required by a machine FEA model to 'absorb' the globally applied temperature for a temperature change representing the maximum variation likely to occur on the machine structure. This time span is termed as the 'settling time' and represents the temperature rise time for the steady state machine model when 'absorbing' the applied temperatures. The settling time is also representative of the minimum time required for on-machine testing which is explained in Section 2.3. This is followed by the second stage of normal environmental simulation that can be used for error modelling and compared with experiment for validation.

To set up the simulation, a standard shop floor temperature of 20 °C was applied as a uniform parameter to the full model of the machine as a 'Predefined Field' in the Abaqus software. Since this paper focuses on an attempt to prove the methodology and maintain relative simplicity in the FEA process, the entire model was applied with the convective heat transfer coefficient of 6 W m^{-2} °C^{-1} [1] which is an averaged value of the various heat transfer coefficients calculated experimentally [1]. It is acknowledged that more detailed application of surface specific coefficients could improve simulation accuracy (see Section 4.2). To estimate the time, the model was simulated until it achieved a temperature change indicative of the variation between the global assumed 20 °C and the applied temperature. A simulation was carried out with 1 °C temperature change to estimate the temperature rise time.

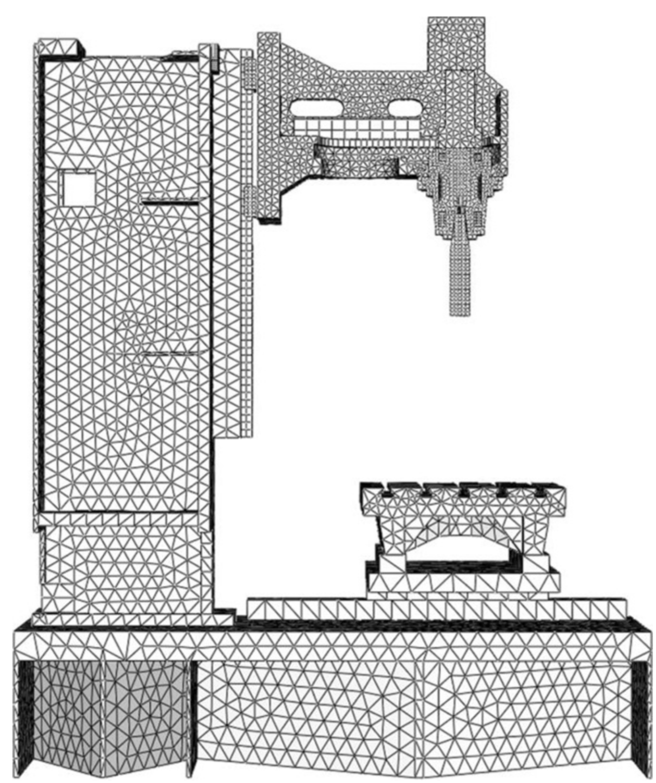

Fig. 2. Meshed model of the machine.

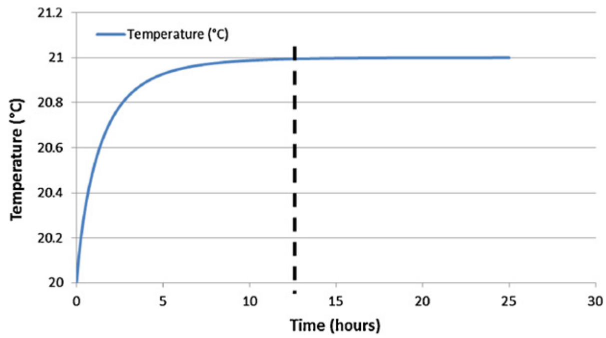

Fig. 3. Settling time of 12.5 h was revealed for this machine's FEA model.

At the end of the simulation the temperature throughout the machine model was uniform; this ensured the selection of a random node to plot the settling time. The simulated result revealed that the machine model achieved 99.99% of the 1 °C temperature change from its initial temperature of 20 °C in 12.5 h as shown in Fig. 3. This settling time suggests that because the machine initial thermal state is unknown at the start of the simulation, this machine FEA model requires this settling time to absorb the applied recorded environmental temperature data at the end of which the temperature distribution should be synchronised with the real machine thermal state.

2.3. Model calibration

The model calibration sequences with the determination of the settling time at the first place. The settling time suggests the minimum environmental testing time required for this machine tool which is an important parameter for both; the production management to estimate the cost-to-production and for the accuracy of FEA results especially when achieving the initial thermal state of the machine FEA model before conducting environmental simulations. Therefore the environmental test to be conducted on the machine must ensure that the settling time is covered. The test then must be continued over a long period such as two or three days to establish the relationship between the machine thermal behaviour and environmental fluctuations occurring within the shop floor during the second stage simulation. The ambient sensors used to record data must be left situated in order to record continuously while the machine is in or off production. Since the determination of the settling time is an offline process therefore practically no machine downtime is required during the model calibration and for the application of this modelling methodology. The temperature sensors can be situated on the machine during any convenient maintenance schedule.

3. Validation of the method

The case study machine, described in 2.1.1, was modelled and calibrated as described. Standard environmental temperature variation error (ETVE) [14] tests were conducted on the 3-axis VMC over a period of a full year not only to validate but to confirm the robustness of the proposed methodology; however samples of data from two seasons (summer and winter) are presented. Three-day (consecutive) testing period was selected to ensure the setting time (12.5 h) data recording as well as to highlight thermal behaviour during normal 24 h periods on a nominally static machine tool. This means that the machine drives were inactive to avoid feedback correction from the position encoders; in essence to obtain the true deformation of machine structure. The model of the machine was not modified in any way during this validation phase.

3.1. Temperature and displacement sensor locations

The machine was already equipped with 65 temperature surface sensors in unique strips [15] for measuring detailed thermal gradients caused by the internal heat sources. Additionally seven surface sensors were placed on the column to track the environmental temperature gradients distribution in this tall structure and one surface sensor on the base. Three ambient sensors were placed inside the machine, at the machine column and adjacent to the base to measure environmental temperature variations. Five non-contact displacement transducers (NCDTs) were placed around a test mandrel to monitor the displacements and tilt of the test mandrel in the *X*, *Y* and *Z* axis directions. A 400 mm post made of invar was used to support the NCDTs. Invar is a steel alloy with a very low coefficient of thermal expansion (1.2 μm m^{-1} K^{-1}) which reduces the effects of changing environmental temperature. Sensor placements are shown in Fig. 4. With reference to the Base sensor, the inside ambient sensor was displaced by approximately 1 m vertically and 0.5 m horizontally while the column sensor was approximately 1.2 m vertically and 2 m horizontally apart.

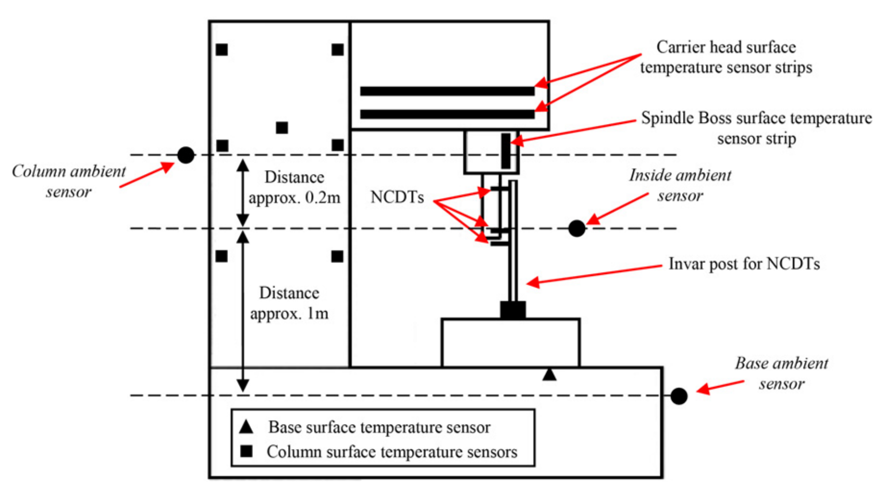

Fig. 4. Temperature and displacement measurement locations.

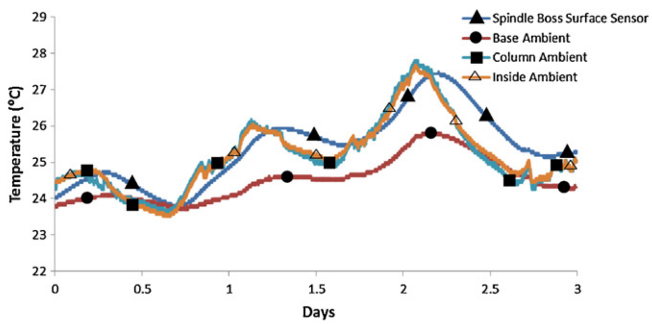

Fig. 5. Temperature profiles obtained over 3 days period (summer test).

3.2. Summer test

The temperature information obtained from the surface sensor on the Spindle Boss and the ambient sensors for a 3 day period are shown in the Fig. 5. At the start of the test, the existence of a vertical temperature gradient around the machine of 1 °C was measured between the base ambient sensor and the column ambient sensor which creates the aforementioned complex initial state. It may also be of interest that the vertical temperature difference between the column ambient sensor and the base ambient sensor fluctuated to approximately 2.5 °C range over the test span which is further evidence of temperature instability within the shop floor environmental temperature arising from various sources such as the day and night transitions. Temperature fluctuations also occur when opening and closing workshop doors.

Fig. 6 shows the measured inside air temperature and the displacement of the mandrel in the *Y*-axis and *Z*-axis. The *Y*-axis displacement followed the temperature variation quite closely whereas the *Z*-axis displacement lagged the temperature by up to 3.6 h at some places. The analysis on the *Y* axis results (using the top and bottom NCDTs) revealed a 30 μm/m tilt present which is likely to have been caused by non-uniform distortions in the complex geometry of the structure resulting in the rapid response to the temperature variation; compared with the slow response of the *Z*-axis which is possibly contributed from pure expansion. The overall displacement range was approximately 12 μm for the *Y*-axis and approx. 28 μm for the *Z*-axis with the overall temperature swing of approximately 4 °C over 3 days. The *X*-axis results were negligible, due to the symmetry of the machine in this direction, and therefore not presented.

This test validates the hypothesis that environmental fluctuation causes thermal distortions in machine structure and proves the deterioration in the accuracy of a machine tool. It was also identified that vertical temperature gradients in a shop floor vary with height which can be critical to large and/or tall machines.

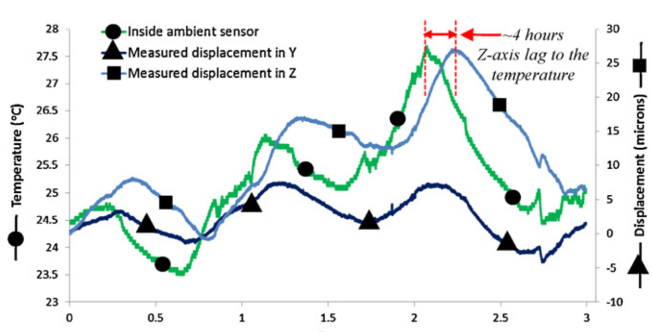

Fig. 6. *Y* and *Z* axes displacements and the environmental temperature measured inside the machine (summer test).

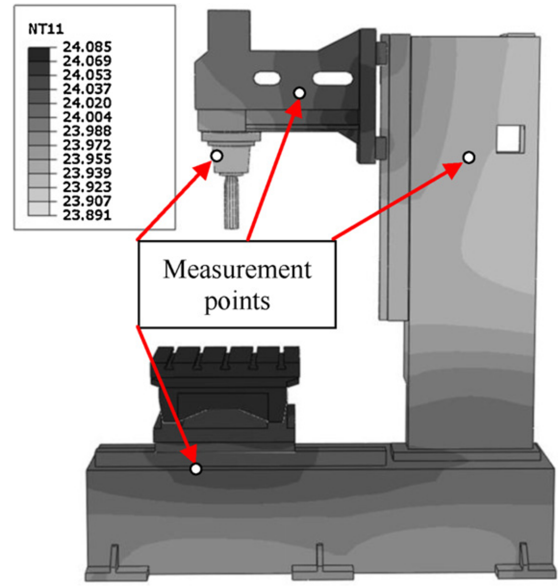

Fig. 7. Temperature gradients across the structure after the first stage (12.5 h) that represent the actual initial thermal state (summer test) – (NT11 – nodal temperatures – °C).

3.3. Validating settling time methodology

The settling time for this machine model was determined to be 12.5 h therefore data covering this time span was selected from the measured ambient data and used in the first stage simulation. As mentioned previously, the temperature data was applied as a transient function in the software using tabular amplitude technique for both simulation stages. Temperature data from the base sensor was applied to the base, information from the inside environmental sensor was applied to the carrier/spindle/tool and the table and temperature information obtained from the column ambient sensor was applied to the column. The result from the first stage simulation must provide not only the correct temperature profile but also the correct thermal memory to match the starting condition of the real machine. It must be noted that the simulations were carried out using only the ambient data which can be captured without machine downtime, the surface sensors are only used to compare and correlate the simulated results. Fig. 7 shows the simulated temperature gradients across the structure after the settling time which should represent the real surface temperature gradients after the 12.5 h span was lapsed. The predicted initial thermal state was revealed to be within ±0.2 °C range measured at points where surface sensors were placed and shown in Table 1

After the settling time simulation, a normal environmental simulation is then run in the second stage using the remainder of the recorded environmental temperature data. The measured and simulated profile results were plotted for the main second stage simulation. The simulated error is obtained as the difference in displacement between the table and the tool (test mandrel). Compared

Table 1
Comparison of measured and simulated surface temperatures after 12.5 h (summer test).

Structure	Measured temperature (°C)	Simulated temperature (°C)
Spindle boss surface	24.1	24
Column surface	24	23.9
Carrier head surface	24.2	24.0
Base surface	23.9	24

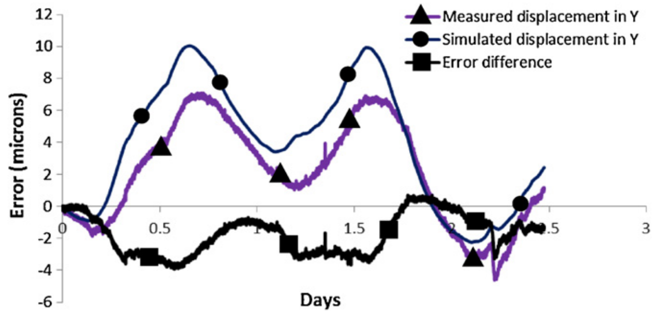

Fig. 8. Correlation between the measured and simulated *Y* axis displacement with settling time removed.

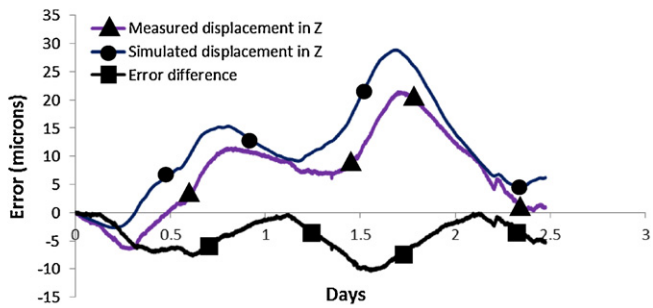

Fig. 9. Correlation between the measured and simulated *Z* axis displacement with settling time removed.

to the measured results, the correlations were 60% for the *Y* displacement profiles (Fig. 8) and 63% for the *Z* displacement profiles (Fig. 9). The residual errors were less than 5 μm for the *Y* axis and less than 11 μm for the *Z* axis. Including the settling time, separate simulations for temperature and displacement took approximately 30 and 40 min respectively (70 min in total). The computer used had typical PC specifications: AMD Phenom 9950 Quadcore 2.60 GHz processor, 4 GB RAM, NVIDIA GeForce 9400 GT graphics card and Windows XP 32bit operating system

4. Winter test

To further validate the robustness of this modelling methodology, another three-day test was carried out to observe the machine behaviour in the winter season. The workshop experienced typical single shift workshop heating patterns often encountered to maintain comfortable environmental temperature for the machine operators. The machine and measurement test conditions were the same as for the summer environment test.

The temperature information obtained from the ambient sensors and the spindle boss surface sensor are shown in Fig. 10. This time the vertical temperature difference between the column ambient sensor and the base ambient sensor fluctuated to approximately 3 °C range over the test span which elaborates that even vertical temperature difference changes within similar vertical distances in different seasons. The spikes are suspected to be from the short periods for opening of workshop doors for deliveries which caused the shop floor environmental temperature to decrease.

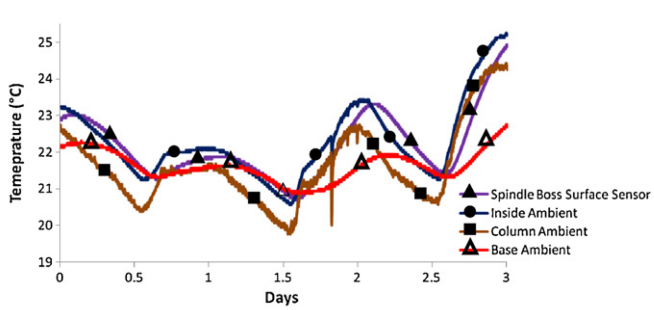

Fig. 10. Temperature data obtained over 3 days period (winter test).

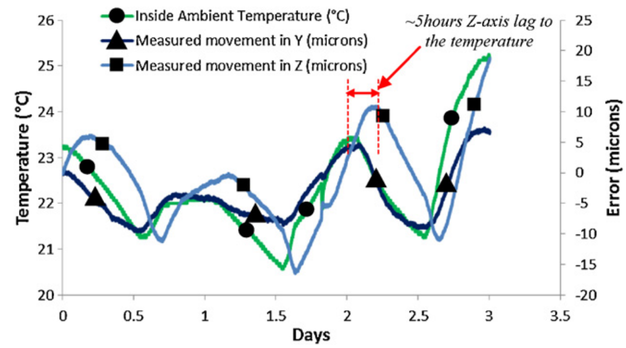

Fig. 11. *Y* and *Z* axes displacements and the environmental temperature measured inside the machine.

Fig. 11 shows the measured inside air temperature and deformation of the machine in the *Y* axis and *Z* axis directions. The movement of both axes followed the temperature variation while the *Z* axis displacement followed but with approximately 5 h lag this time. The overall movement is 18 μm in the *Y* axis and 35 μm in the *Z* axis for an overall temperature swing of approximately 5 °C over the 3 days. This increase was expected because of the exaggerated day and nights heating transitions.

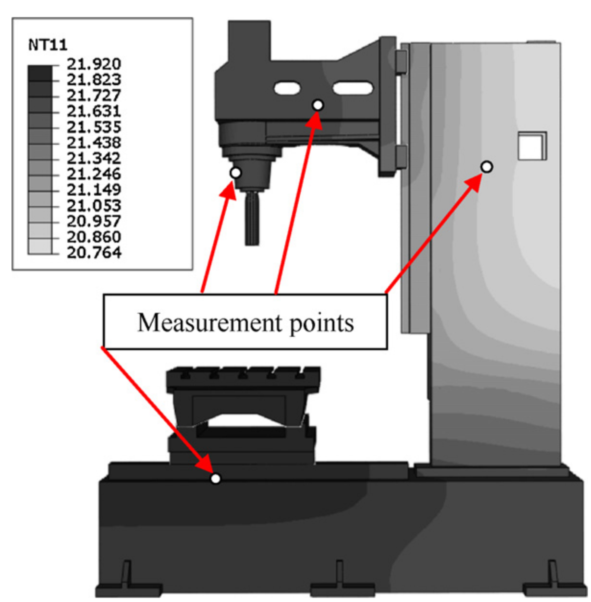

Fig. 12. Temperature gradients across the structure after the first stage (12.5 h) that represent the actual initial thermal state (winter test).

Table 2
Comparison of measured and simulated surface temperatures after 12.5 h (winter test).

Structure	Measured temperature (°C)	Simulated temperature (°C)
Spindle boss surface	21.7	21.7
Column surface	21	20.9
Carrier head surface	21.6	21.6
Base surface	21.9	21.9

Table 3
Summary of the results.

	Y drift (μm)	*Y* model error (μm)	*Y* improvement (%)	*Z* drift (μm)	*Z* model error (μm)	*Z* improvement (%)
Summer	12	4.6	60	28	10	63
Winter	18	6.3	63	35	11.7	67

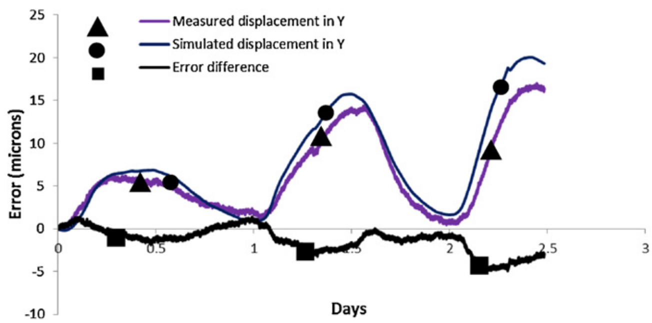

Fig. 13. Correlation between the measured and simulated *Y* axis displacement with settling time removed.

4.1. FEA simulations (offline assessments – winter test)

A similar procedure was followed for simulating the model. For the first stage, 12.5 h of the recorded data was used for the settling time as before, followed by the environmental simulation in the second stage. Fig. 12 shows the simulated temperature gradients across the structure after the settling time which represents the real surface temperature gradients after the 12.5 h span was lapsed. The predicted initial thermal state was revealed to be within ±0.2 °C range measured at points where surface sensors were placed and shown in Table 2.

4.1.1. Winter test correlations

The simulated results correlate well with the measured profile being 63% for the *Y* movement profiles (Fig. 13) and 67% for the *Z* movement profiles (Fig. 14). The residual errors were less than 7 μm in *Y* and less than 12 μm in *Z*.

The winter test not only validated the capability of the modelling methodology but also confirmed its robustness. Development of the CAD model, obtaining the settling time and FEA environmental simulations are conducted offline. The temperature sensors can be installed in any convenient maintenance schedule and environmental temperature data can be recorded while the machine in production therefore is non-invasive to production and cost effective as generally no machine downtime is involved. It is also highlighted that 12.5 h of settling time can be representative of a minimum time required for temperature data acquisition which can be recorded while the machine is in production.

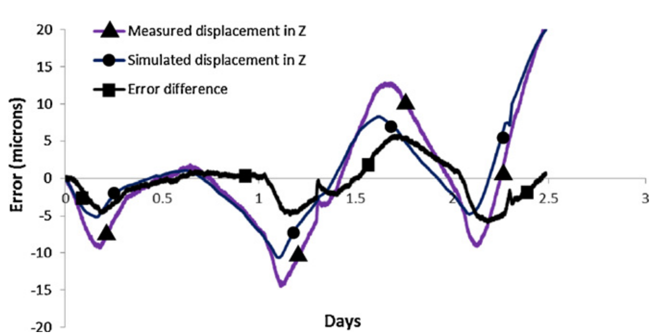

Fig. 14. Correlation between the measured and simulated *Z* axis displacement with settling time removed.

4.2. Summary of results

An FEA-derived thermal model of the machine was created in the summer using a 12.5 h settling time methodology. This methodology has been validated over a year period, with results from two Three-day tests (summer and winter) presented here. Table 3 summarises the results.

It can be observed that compared to good temperature correlations (>90%), the predicted positioning of the machine matched within 60–67% range with the measured movement. This is suspected to be due to the averaged heat transfer coefficient values used in this case study for the FEA model. It is anticipated that the positioning results can correlate better when the FEA model is applied with surface specific heat transfer coefficients that vary around enclosed voids creating air pockets that will vary in temperature independent to the bulk ambient temperature [1].

5. Conclusions

Environmental thermal testing is often avoided in industries due to the costs and inconvenience associated with machine downtime. This paper presented a novel offline environmental thermal error modelling method based on FEA that successfully deals with the machine downtime issue using a two-stage simulation method, short on-line testing period and non-disruptive offline temperature monitoring. The sequence of the method is to create a CAD model of the machine, determine the settling time of that machine model and create initial conditions in the first stage followed by the environmental simulation in the second stage. The settling time ensures the minimum time is spent on data acquisition. Temperature sensors can be installed on the machine during any convenient scheduled machine maintenance and the simulations can be done within an hour or two, so it is highly efficient. The methodology was successfully validated on a 3 axis vertical milling machine tool over a year period; samples of data from two ETVE tests during two seasons (summer and winter) are presented where the critical nature of the fluctuating shop floor environment and its effect on machine tool precision were also highlighted. The results revealed good correlations between the experimental and FEA simulated results typically between 60% and 70%. The modelling methodology has significantly reduced the machine downtime required for a typical environmental testing from a fortnight to only hours. Practically no machine downtime is associated with the application of this modelling methodology except for short validations (if required). Additional useful information can be obtained for predicting the effects of speculative conditions.

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