Mian, Naeem, Fletcher, Simon, Longstaff, Andrew P., Myers, Alan and Pislaru, Crinela

Efficient offline thermal error modelling strategy for accurate thermal behaviour assessment of the machine tool.

Original Citation

Mian, Naeem, Fletcher, Simon, Longstaff, Andrew P., Myers, Alan and Pislaru, Crinela (2009) Efficient offline thermal error modelling strategy for accurate thermal behaviour assessment of the machine tool. In: Proceedings of Computing and Engineering Annual Researchers' Conference 2009: CEARC'09. University of Huddersfield, Huddersfield, pp. 26-32. ISBN 9781862180857

This version is available at http://eprints.hud.ac.uk/6857/

EFFICIENT OFFLINE THERMAL ERROR MODELLING STRATEGY FOR ACCURATE THERMAL BEHAVIOUR ASSESSMENT OF THE MACHINE TOOL

N. S. Mian[1], S. Fletcher [1], A. P. Longstaff [1], A. Myers [1], C. Pislaru [1]
[1] University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

ABSTRACT

Positional accuracy of the machine tool is affected by the instabilities caused by the thermal gradients produced from the internal and external heat sources. Thermal gradients cause linear and non linear thermal expansions of the complex machine parts which result in the generation of the positional error between the tool and the work piece affecting the machining accuracy. Thermal gradients due to internally generated heat and varying environmental conditions pass through structural linkages and mechanical joints where the roughness and form of the contacting surfaces act as resistance to thermal flow and affect the heat transfer coefficients. Measurement of long term thermal behaviour and associated thermal deformations in the machine structure is a time consuming procedure and most often requires machine downtime and is therefore considered a dominant issue for this type of activity, whether for characterisation or correction. This paper presents the continuation of the efficient offline technique using Finite Element Analysis (FEA) to simulate the combined effects of the internal and external heat sources on a small vertical milling machine (VMC). The complete simplified CAD models of the machine were created and used to simulate the thermal behaviour of the machine structure by using the evaluated experimental data. The FEA simulated results obtained are in close correlation with the obtained experimental results which enables the offline thermal assessments for short and long term thermal behaviour and the extraction of the nodal thermal information for the development and enhancements of robust thermal compensation models.

1. INTRODUCTION

Machine tool structures are susceptible to temperature changes which occur due to the heat produced internally from machining processes and externally from environmental changes. The heat flows through the structural elements and produces inevitable temperature gradients which cause deformations often in a very complex manner, resulting in unwanted displacements of the cutting tool relative to the work piece known as thermal errors. It has been reported that thermal errors can represent 70% of the total volumetric error (Bryan J, 'International status of thermal error research' Ann. CIRP, 39, 645-656, 1990.)). Three main causes of structural temperature changes are 1) Internal heat generation with possible heating sources such as bearings, motors, belt drives etc. 2) Environmental variations with possible heat sources such as direct sunlight, workshop heating etc. Typically in non-temperature controlled environments, the 24 hours day and night cycle resulting from these sources are the most dominating long term variations. 3) Radiant heating with possible sources such as infrared workshop heating, direct sunlight striking the machine.(Ramesh (2000)

A broad range of research has been carried out to compensate thermal errors. (Mian (2008)) discussed the usage of techniques such as Neural Networks, linear regressions, multiple linear regression and Finite Element Analysis (FEA) with their capabilities, results and complexities associated with machine downtime and cost. It was also discussed that FEA has been used as part of the research as a validation tool on discrete structural elements but not on a full CNC machine for thermal compensation however it has proved its significance in predicting thermal errors in reduced time scales which leads to reduced machine downtime. (Mian (2008)) showed machine tool offline thermal assessment strategy using FEA which can reduce machine downtime. Assessment was carried on assembled machine CAD models of the spindle, carrier head, bearings tool and column of a small vertical milling machine. Abaqus 6.7-1 (Dassault Systemes (2007)) simulated results showed well matched simulation results with experimental tests for one hour heat and one hour cool down. In order for this strategy to be able to predict results more accurately and efficiently, it was required to use this strategy on the full optimized machine model with simulations for longer periods to match the long term industrial operating conditions.

2. THERMAL CONTACT RESISTANCE TESTING

Heat flows through machine structure and passes through structural joints and contacts. (Mian (2008)) showed TCR testing results using two steel plates tested in dry and oiled conditions to replicate the precision and accuracy used in assembly of the relevant components of a typical machine tool. The results were used to carry out accurate FEA simulations. TCR values were calculated using equation 1.

$$h_c = \frac{QK}{\left(AK\Delta T - 2Q\Delta L\right)} \quad \textbf{(1)}$$

Where h_c is TCR and K is the conductivity of steel, Q is the heat energy, ΔT is temperature difference and ΔL is the distance.

3. ABAQUS MODELS

Optimised and idealised machine models of base, table and saddle were created and assembled with previously created models (Mian (2008)) to a full machine model. Idealization includes halving of the full model due to its symmetrical nature over X axis. Figure 8 and 1.1 shows the full and halved machine CAD model. Bearings, belt drives and motor supporting structure were simplified and represented as heat generation sources in the machine CAD model.

4. MACHINE TOOL TESTING

For more accuracy in results obtained (Mian (2008)), it was required to devise an efficient strategy to calculate the convective heat transfer coefficient (h) due to airflow across test mandrels or even generic tooling. A thermal imaging camera was set up to view the spindle and mandrel rotating at 4000rpm. The heating and cooling cycle data was recorded with high speed imaging (per second). The values obtained were 47W/m^{2}C and 6W/m^{2}C respectively which were used to simulate thermal distribution across the mandrel.

4.1 Thermal and displacement testing (Online test)

Optimised values for heat transfer coefficients were applied to the machine based on new experimental results. One hour heat and one hour cooling test was repeated and the spindle was rotated at 4000rpm. Thermal data was recorded using 61 thermal sensors in strips located at the surface of the carrier and spindle boss considered as thermal key points explained by (White (2001)). Thermal imaging was also used to capture temperature data at the surface and places where thermal sensors are hard to install. Five Non Contact Displacement Transducers (NCDTs) were placed around a test mandrel (see Figure 11) to monitor the displacements of the tool in X, Y and Z axes during the test. The results obtained are presented in section 5.1 (Figure 12 and 13) for reviewing them in direct comparison with the obtained simulated profiles. Figure 9 shows the thermal sensors location on the machine. Figure 10 shows the thermal image showing thermal distribution in the spindle motor and the belt drive.

5. ABAQUS SIMULATIONS (OFFLINE ASSESSMENTS)

The thermal information was converted into thermal loads for applying as body heat flux generated from the heat sources in the software and TCR values (Mian (2008)) were applied at the assembly contacting surfaces and the simulation was set for 1 hour heating and 1 hour cooling.

5.1 Temperature and Displacement Simulations (Offline assessment)

Temperature and displacement results were extracted from the nodes located at similar positions to the actual sensor locations on the machine (both thermal sensors and NCDTs). The results showed improved accuracy in temperature and displacement profiles compared with previous results [3]. Simulation time was also reduced to 3 minutes and 7 minutes for thermal and displacement analyses in Abaqus respectively. Figure 12 shows the simulated temperature distribution in the spindle carrier assembly and Figure 13 shows the simulated machine behaviour due to thermal distribution. A very good correlation of 94% was obtained for full temperature profile and 71.62% for the full displacement profile shown in Figure 14 and Figure 15. Where black profile shows the correlation between the experimental and simulated results.

6. LONG TERM TESTS

As machine down time is involved with carrying out extended thermal trials on production machine tools, one of the greatest advantages of improving offline simulation capability is to enable characterisation of the machine to a reasonable accuracy over medium and long term periods over which, on-machine testing becomes impractical. The machine was set for a heating test with spindle rotated at 4000rpm constant speed for 3 hours followed by 2 hours cooling phase. Figure 16 and Figure 17 shows the correlation graphs of experimental and simulated temperature and displacement profiles respectively. The Abaqus simulation took 5 minutes for thermal and 10 minutes for displacement analysis. Again good correlation of 75.46% was obtained for the full temperature profile and 82.17% for the full displacement profile.

6.1 Step Heat and Cool Test

The complexity of the duty cycle was increased to more closely match operating conditions over much longer test periods. The spindle was rotated in steps at 4000rpm with two 2 hours heating cycles with 1 hour cooling gap in between left for 3 hours cooling phase at the end. The total test length was 8 hours. Figure 18 and Figure 19 shows the correlation plots of experimental and simulated temperature and displacement profiles respectively. The Abaqus simulation took 8 minutes for thermal and 12 minutes for displacement analysis. Again good correlations of 72% can be observed for the full temperature profile and 73.3% for the full displacement profile.

7. ENVIRONMENTAL TESTING

The machine was monitored for continuously 3 days for deformations which occurs due to the change in environmental temperatures. Numbers of temperature sensors increased and were placed at mandrel's surface, table surface, column top and two sensors placed inside the machine to measure ambient temperature variations. Ambient temperatures were used to calculate convective heat transfer coefficient inside the machine enclosure and was obtained 6W/m^{2}C. The displacement was measured at mandrel's Z direction. Figure20 shows experimental temperature profiles obtained for 3 days. The overall temperatures varied approx. ±4˚C at the head assembly and approx. ±2˚C at the bed (base) during the 3 day period. The results confirm that the environmental temperature variations exist and play an important role in producing thermal drifts over longer production periods.

Figure21 shows the inside air temperature and displacement at the mandrel where displacement followed the temperature variation and varied approx ±28 microns in z direction over 3 days. This gives a clear picture of machine structure bending sensitivity to environmental variations. The displacement profile's lag is due to the response time of the structure to the temperature variation. Data obtained from environmental testing was applied into Abaqus along with the convective heat transfer coefficient measured. Simulation for thermal and displacement testing took 15 and 22 minutes respectively. Figure 22 shows the correlation plot of the experimental and simulated displacement profiles. Again very good correlation of 64.2% can be observed for the full displacement profile which shows the FEA technique's capability to predict the long term environmental temperature variations and its associated error offline, hence reducing significant amount of machine downtime.

8. CONCLUSIONS

The distribution of the thermal gradients and the thermal error caused in a small VMC CNC machine tool was studied and analysed experimentally and predicted offline using FEA techniques. Thermal behaviour of the machine was examined by running the machine for certain times and carefully extracting detailed temperature and displacement data. Further on the machine was tested for long term heating and cooling cycles using only the data from initial short terms tests (one hour). Environmental testing was carried out over a 3 day period to record temperature variations and thermal drifts. The results obtained from experiments were analysed and applied in the FEA simulation software Abaqus 6.7-1. The FEA results matches very well with the experimental results obtained. The simulated FEA technique enabled offline assessments of the temperature distribution and displacements in a machine tool reducing machine non productive downtime and can provide significantly more thermal data for the creation and validation of robust long term thermal error compensation models.

9. REFERENCES

Bryan J, 'International status of thermal error research' Ann. CIRP, 39, 645-656, 1990.

Ramesh R., Mannan M.A, Poo A.N, 'Error compensation in machine tools – a review Part II: thermal error', International Journal of Machine Tools & Manufacture, v40, pp 1257-1284, 2000.

Mian N.S, Fletcher S, Longstaff AP, Myers A, Pislaru C, ‘Novel and efficient thermal error reduction strategy for machine tool performance improvement’, CEARC’08, November 2008, University of Huddersfield, ISBN: 978-1-96218-067-3.

Dassault Systemes 2007, ABAQUS 6.7-1 FEA software, ABAQUS, Inc.

White AJ, Postlethwaite SR and Ford D, ’Measuring and Modelling Thermal Distortion on CNC Machine Tools’, Fifth International Conference on Laser Metrology and Machine Performance-Lamdamap 2001, University of Birmingham, pp 69 – 79.

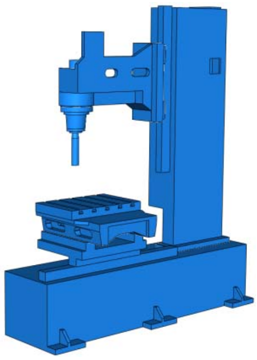

Figure 1: Full machine CAD model created in ABAQUS 6.7-1

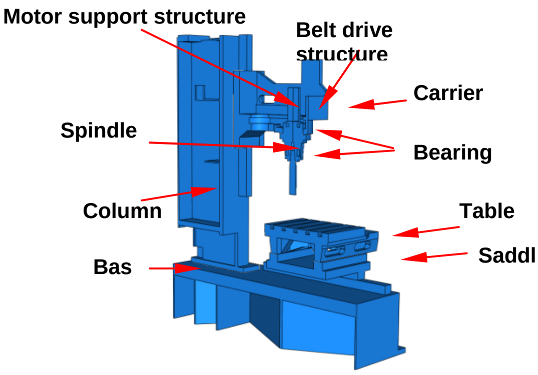

Figure 1.1: Halved model (Symmetry)

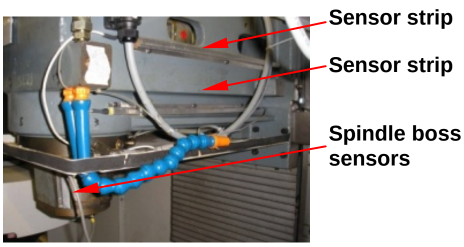

Figure 2: Thermal sensors location machine

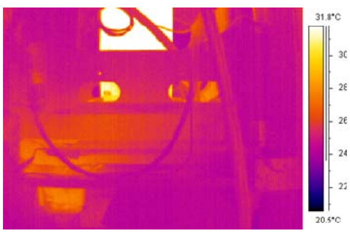

Figure 3: Thermal distribution in the Carrier head

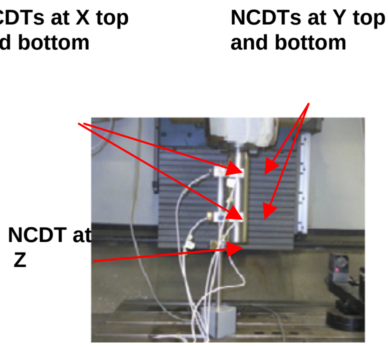

Figure 4: NCDTs located around on the the tool

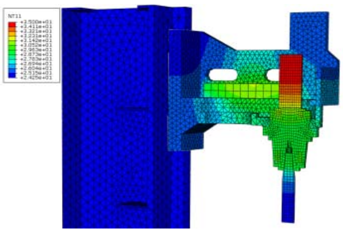

Figure 5: Temperature distribution in the machine structure during heating cycle. (Red=hot, Blue=cold)

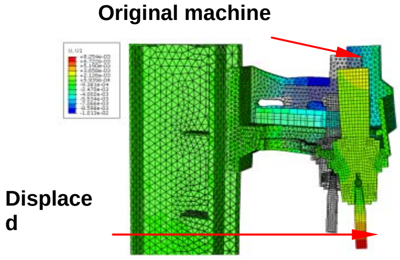

Figure 6: Deformations in the machine due to thermal distribution

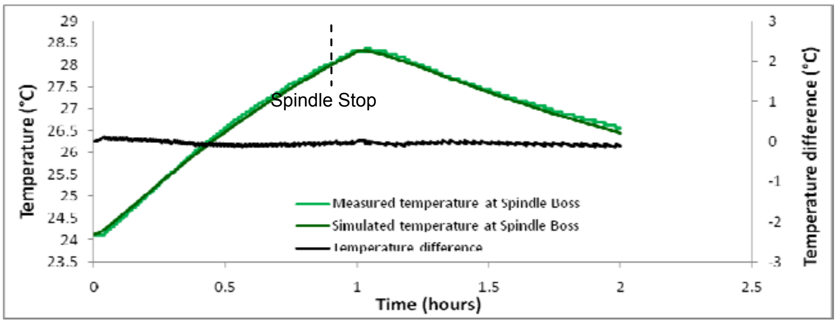

Figure 7: Correlation plot of the experimental and simulated temperature profiles

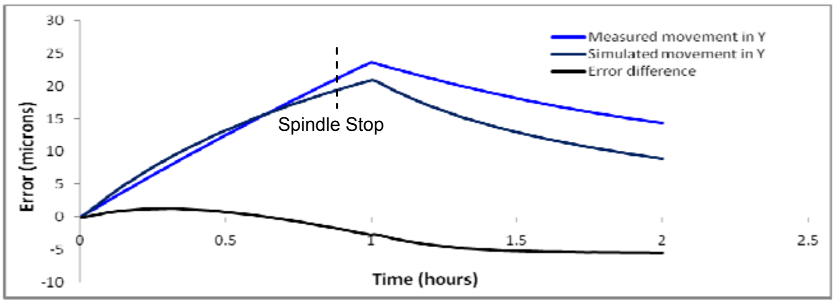

Figure 8: Correlation plot of the experimental and simulated displacement profiles

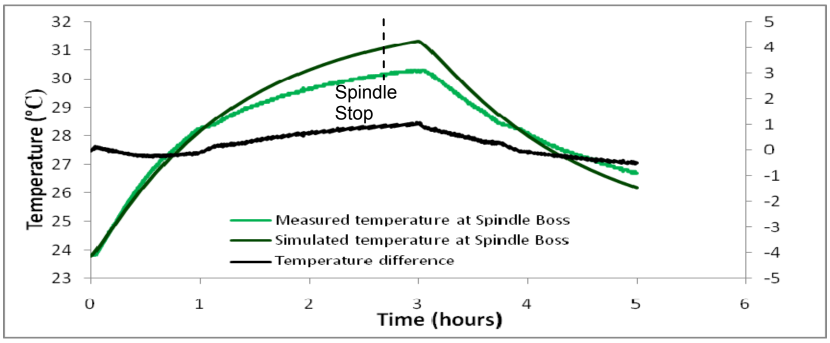

Figure 9: Correlation plot of the experimental and simulated temperature profiles (long term test)

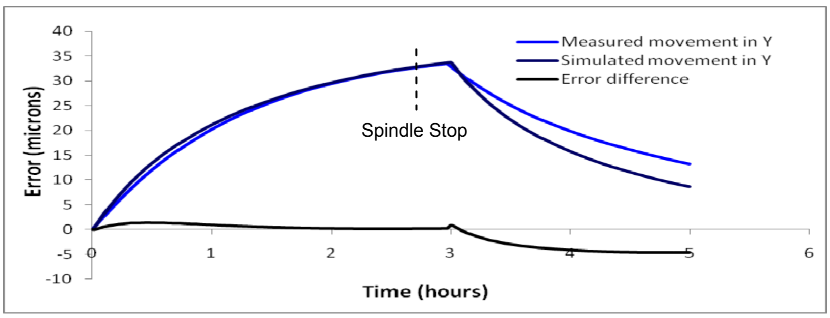

Figure 10: Correlation plot of the experimental and simulated displacement profiles (long term test)

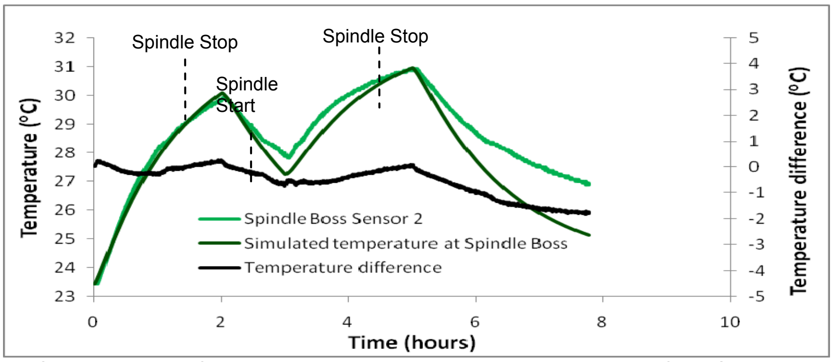

Figure 11: Correlation plot of the experimental and simulated temperature profiles (Step heat/cool test)

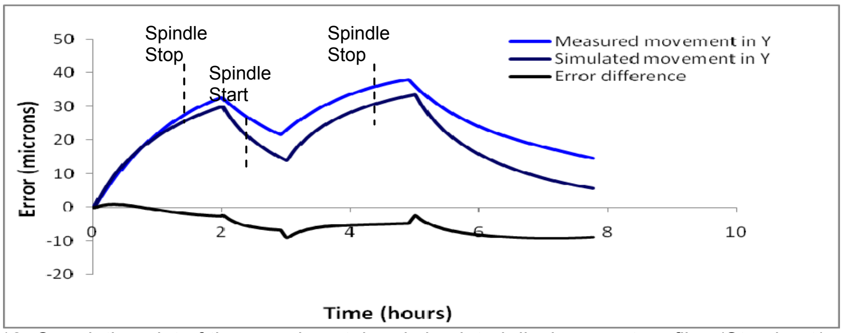

Figure 12: Correlation plot of the experimental and simulated displacement profiles (Step heat/cool test)

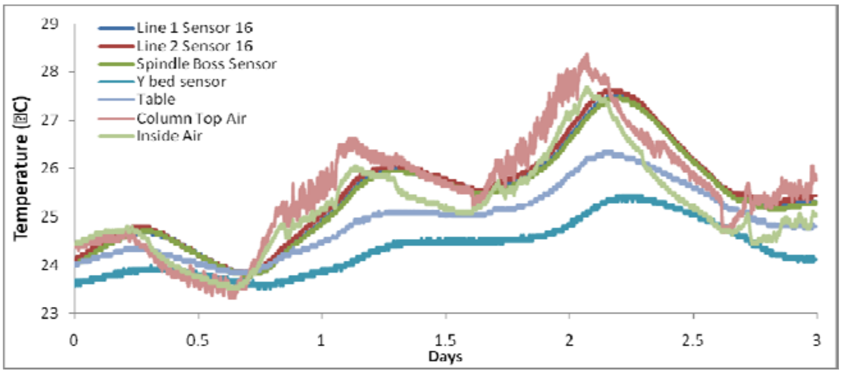

Figure13: Environmental temperature variations recorded over 3 days

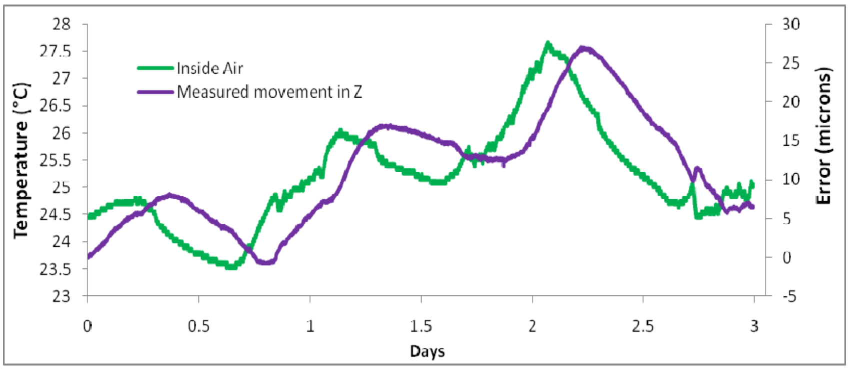

Figure14: Experimental temperature and displacement profiles recorded over 3 days at mandrel's Z axis

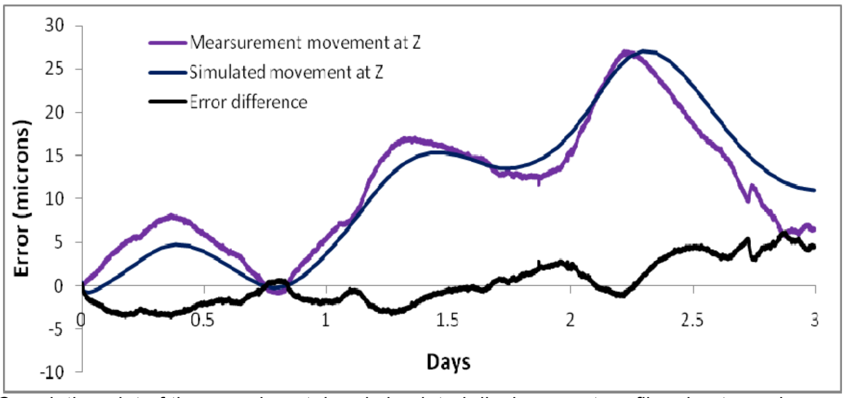

Figure 15: Correlation plot of the experimental and simulated displacement profiles due to environmental swings