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Real-time thermal error compensation module for intelligent Ultra Precision Turning Machine (iUPTM)

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Abstract

Accuracy & precision are the main requirements for ultra precision machine tools. Many factors affect the performance of the system that in turns affect the product quality. Among all sources of errors, the thermo mechanical deformation errors are the main contributor for the overall geometrical errors. This paper mainly aims at establishment of methodology to compensate thermal deformation errors in real-time for ultra precision machine tools. The real-time thermal error compensation module has been developed and integrated to intelligent Ultra Precision Turning machine. The module includes temperatures as inputs, neural network algorithm for computing the thermal deformations errors, 'C' programming for real-time calculations and integration with open architecture CNC controller. The module runs in silent mode which avoids human intervention for correction of thermal deformation errors.

Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)
Keywords: Ultra precision machine tools; Thermal error compensation; Open architcture CNC controller; Diamond turning; Neural networks.

1. Introduction

The thermo mechanical deformation of machine tools, caused by external and internal heat sources, is one of the main contributors to the overall geometric error of the workpiece. Machine tool manufacturers therefore try to reduce the thermal displacements by R. Ramesh et al (2000).

Nomenclature

T1-T6	Temperature sensors
X, Z	Axis displacements errors

Researchers have considered ways of reducing thermal error, including the thermally symmetric design of a structure, separation of the heat sources from the main body of the machine tool, cooling of the structure, and so forth by R. Ramesh et al (2000). However, the manufacturing costs associated with the above approaches will be very high if the accuracy requirements are beyond some level. Also in many cases physical limitations to accuracy, this cannot be overcome solely by design techniques. Therefore it is well known that the most cost-effective way of achieving high quality products with high productivity is by the use of the error compensation techniques (ECT).Thermally induced errors can account for as much as 70% of the dimensional errors of a workpiece by Wu Hao and Zhang Hongtao (2008). Precise modeling of errors is a critical part of error compensation.

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2. Flow Chart

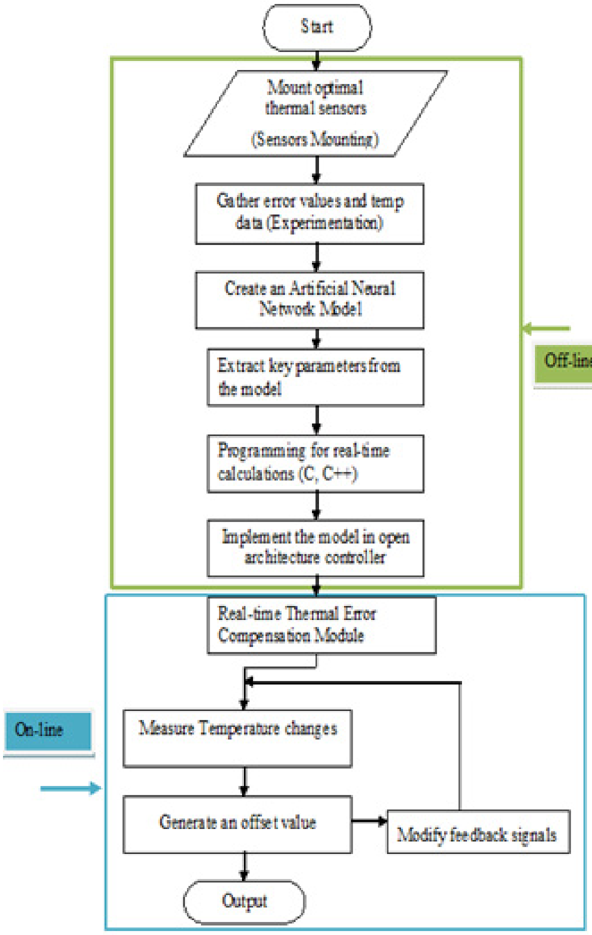


Fig1: Flowchart of thermal error compensation module

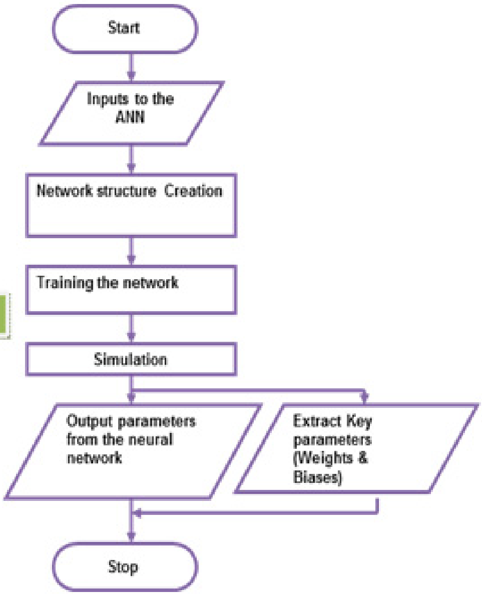


Fig2: Neural Network Module for algorithm development

3. Procedure for Development of Real-Time Thermal Error Compensation Module

The procedure consisted of five major steps:

1. Configuring the capacitive sensors , temperature sensors and the Ultra Precision machine control to measure the thermal deformation errors of X and Z axis.
2. Experimentation on the Ultra Precision machine using thermal setup and capacitive setup for collecting the temperature data & thermal deformation errors in both X and Z axis based on ISO-230-3:2001.
3. Designing the neural network and training it with the measured data.
4. Extracting the key network parameters (weights and biases) and programming the real-time calculations.
5. Repeating the measurement test to determine real-world performance of the system on the machine.

Three experiments were carried out on iUPTM to map the thermal errors:

1. Environment Temperature Variation Error (ETVE) test
2. Test to measure thermal expansion during spindle run
3. Test to measure thermal expansion during axis runs

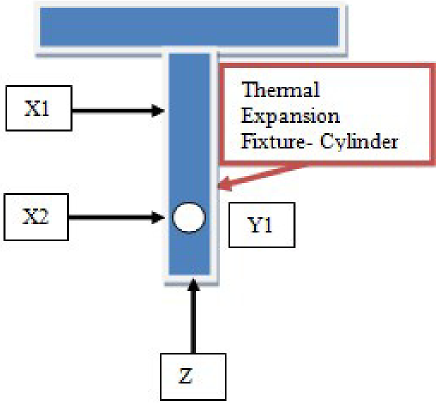
4.1. ETVE Test

This test reveals the effects of environmental temperature changes of the iUPTM and to estimate the thermally induced errors in X (X1 & X2), Y & Z axis during X & Z Axis on, Chiller ON/OFF, AC ON/OFF & Spindle OFF

Table1: Measurement conditions for ETVE test

Parameter	Condition	Remarks
X Axis	ON	No Movement
Z Axis	ON	No Movement
Spindle	OFF	Spindle off throughout the measurement
Chiller	ON & OFF	Two measurements were carried out with Chiller ON & OFF
AC	ON & OFF	Two measurements were carried out with AC ON & OFF
Time	4 Hours	-

4.1.1. Test Method



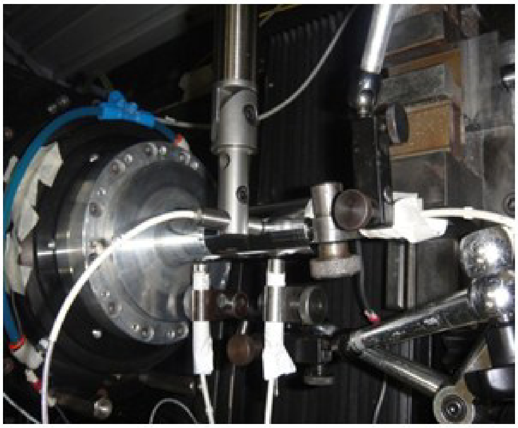


Fig3: Schematic showing the capacitive sensors mounted on the machine Fig4: Experimental setup of ETVE test showing capacitive sensors

For this test, the fixture in which linear displacement sensors are mounted on the X & Z axis securely fixed to the non-rotating tool-holding zone of the iUPTM machine so as to measure the following:

- The relative displacements between the component that holds the tool and the component that holds the workpiece along the three orthogonal axes parallel to the axes of travel of the machine as shown in the fig(2);
- The tilt or rotation around the X axis of the machine tool.

4.2. Test to measure thermal expansion during spindle run:

This test is carried out to identify the effects of the internal heat generated by rotation of the spindle and the resultant temperature gradient along the structure on the distortion of the machine structure observed between the workpiece and the tool.

4.2.1. Test Method:

For this test, the fixture in which the linear displacement sensors are mounted shall be securely fixed to the non-rotating workholding or tool-holding zone of the machine so as to measure the following:

- The relative displacements between the component that holds the tool and the component that holds the workpiece along the three orthogonal axes parallel to the axes of travel of the machine
- Tilts or rotation around the X & Y axes of the machine tool

Table2: Measurement conditions for spindle growth test with spindle running

Parameter	Condition	Remarks
X Axis	ON	Movement
Z Axis	ON	Movement
Spindle	ON	Spindle on throughout the measurement. Spindle RPM:1500 Spindle RPM: Variable RPM
Chiller	ON & OFF	Two measurements were carried out with Chiller ON
AC	ON & OFF	Two measurements were carried out with AC ON & OFF
Measurement time	4 Hours	-

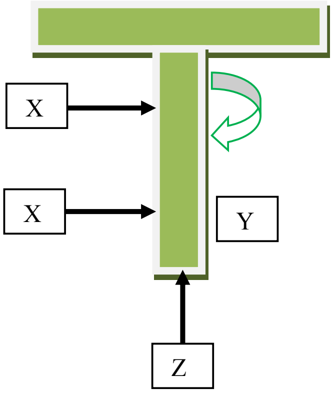


Fig5: Schematic showing the capacitive sensors mounted on the machine with spindle rotating

The spindle speed spectrums selected based on the machining conditions generally used in iUPTM. The choice of the test procedure with spindle speed spectrum and the percentages were specified based on iUPTM.

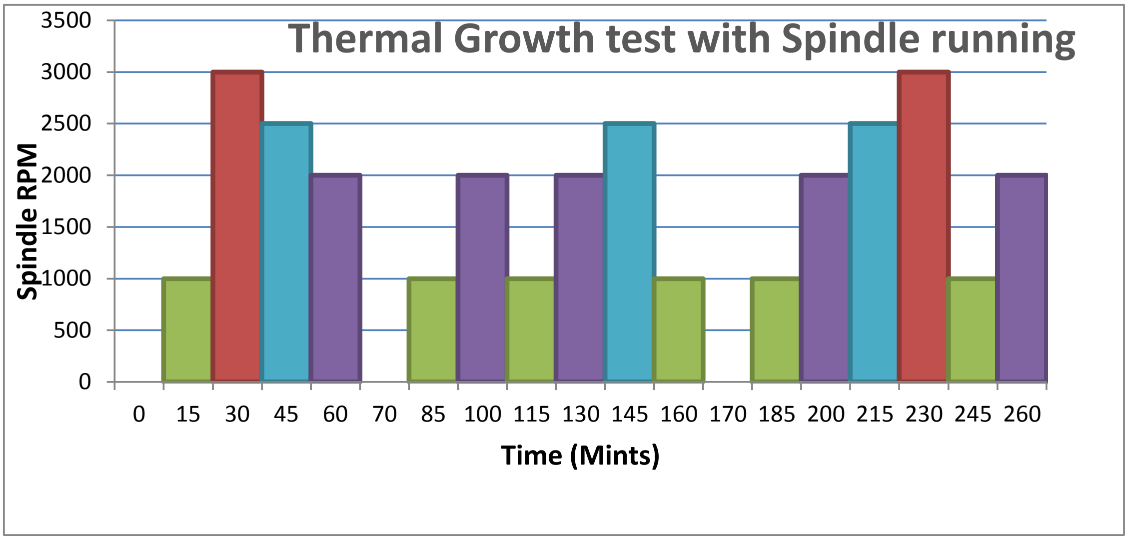


Fig6: Thermal Growth measurement with respect to spindle running conditions

4.3. Test to measure thermal expansion during axes run

This test is carried out to identify the effects of internal heat generated by the machine positioning system on the distortion of the machine structure observed between the workpiece and the tool. The test indicates the amount of drift at two positions along a machine linear axis.

Table3: Measurement conditions of thermal distortions due to Axes run

Parameter	**Condition**	**Remarks**
X Axis	ON	No Movement
Z Axis	ON	No Movement
Spindle	ON	Spindle on throughout the measurement
Chiller	ON	Two measurements were carried out with Chiller ON
AC	ON & OFF	Two measurements were carried out with AC ON & OFF
Time	4 Hours	-

4.3.1. Test Method:

The target positions have been selected close to the end of X & Z axis. The target positions 3 & 4 corresponds to 'X' axis end positions with a gap of 170 mm between each position. The target positions 1 & 2 corresponds to fixed positions of 'Z' axis. It is ideal to carry out the thermal distortion measurements in two extreme points of the axes, this setup has taken care for 'X' axis at two extreme positions but for 'Z' axis it is only one position

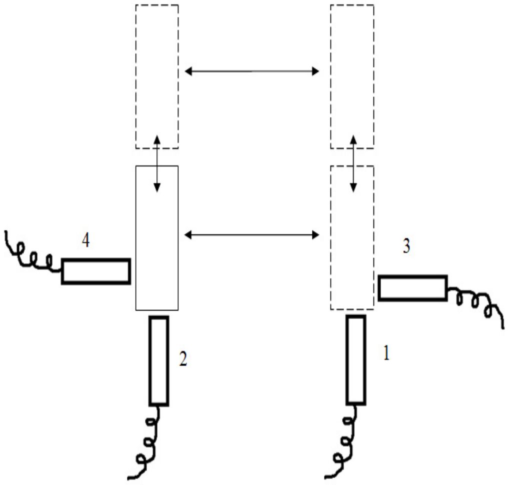


Fig7: Schematic showing the capacitive sensors arrangement for axis thermal growth

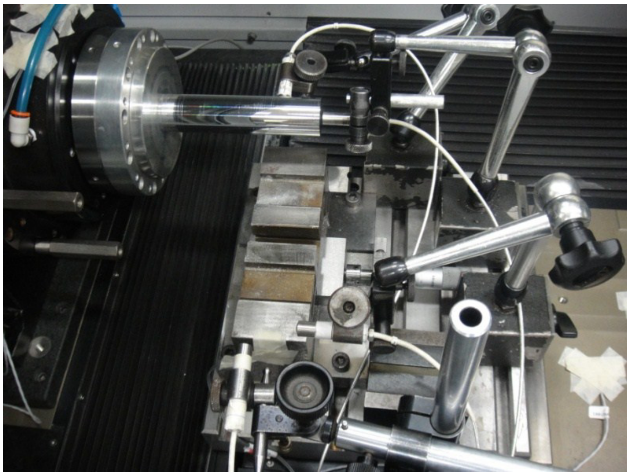


Fig8: Thermal error measurements for axis run setup

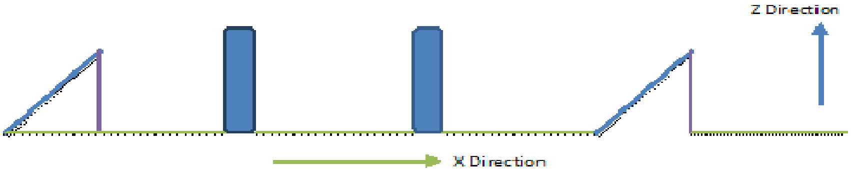


Fig9: Thermal load pattern conditions of X & Z axis runs

5. Results & Discussion:

The data has been selected based on the machine conditions generally used in iUPTM. The below data is used for training the neural network. From the above experiments, one set of data has been taken to develop a real-time thermal module and compensate the thermal errors in real-time for an iUPTM machine.

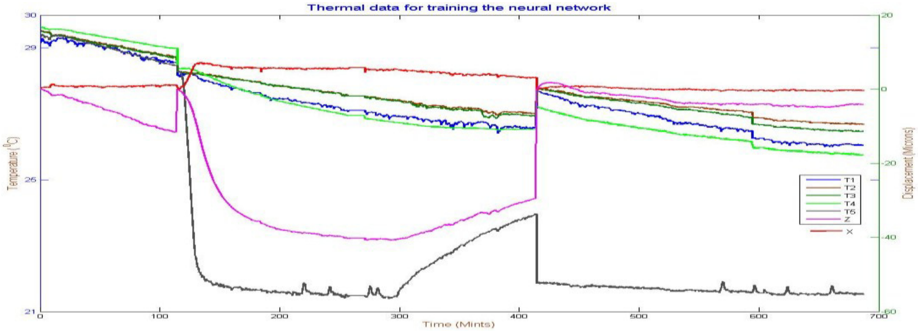


Fig10: Training data for the neural networks

5.1. Block diagram:

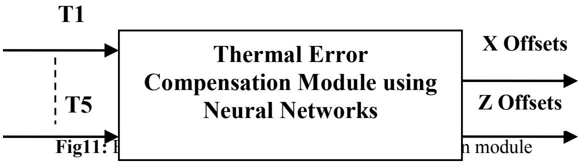


Fig11: n module

5.2. Pre-processing & post processing of data:

The experimental data has been processed to filter out unwanted data, the processed data has been used for neural network training. Neural network training can be made more efficient by performing certain pre-processing steps on the network inputs (Temperatures) and targets (X & Z thermal deformation error). The normalization step is applied to both the input vectors and the target vectors of the experimental data set. The *"minmax"* function has been used for normalization. The network output can then be reverse transformed back into the units of the original target data when the network is put to use in the field.

5.3. Scaling:

Input scaling:

Min Max
y= m*x +c; y: {-1, 1} **Temperature Minimum:**T1=26.006, T2=26.682, T3=26.469, T4=25.738 & T5=21.386
x= [T1, T2…..T6]; **Temperature Maximum:** T1=29.318, T2=29.525, T3=29.507, T4=29.628 & T5=29.421

Output Scaling:

Min Max
y=m*x+c; x= {-1, 1}; **Thermal deformation errors Minimum:** X=7.2383 & Z=1.8454
y=[X, Z]; **Thermal deformation errors Maximum:** X=-0.65 & Z=-40.806

5.4. Neural Network algorithm development:

The feed-forward neural network has been used to find the relationship between temperatures & displacement values. The feed-forward neural network is used for fitting the non-linear thermal data. The network architecture is selected based on the size & type of thermal data. The number of layers and neurons are selected based on trail & error method by seeing regression plots and performance. The performance of the neural network is tested based on the mean square error. The goal of the neural network is 0. The performance of the neural network algorithm has been developed using Neural Network Toolbox in Matlab R2012. The multilayer feed forward backpropogation algorithm with training algorithm "trainlm" has been used to develop a thermal error compensation model. The neural network architecture is shown in below fig.12, performance measure shown in below fig.13a, regression plot shown in fig.13b, neural network training shown in fig.13c.

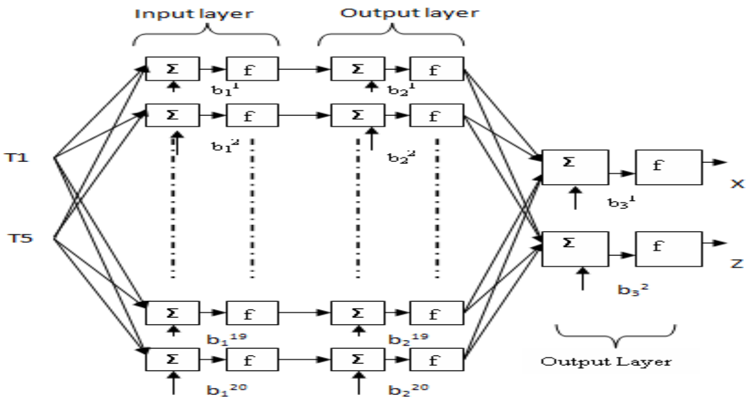
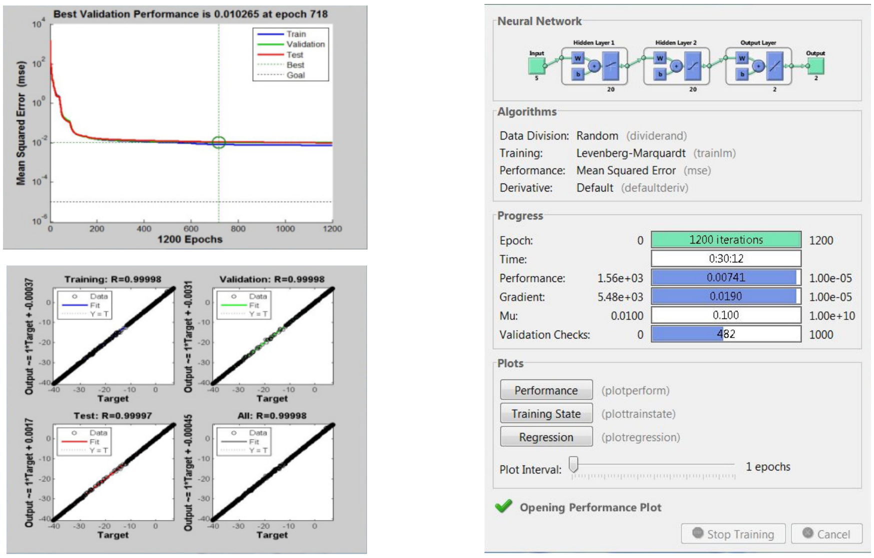


Fig12: Neural network architecture



Data Division: Random (dividerand)
Training: Levenberg-Marquardt (trainlm)
Performance: Mean Squared Error (mse)
Derivative: Default (defaultderiv)

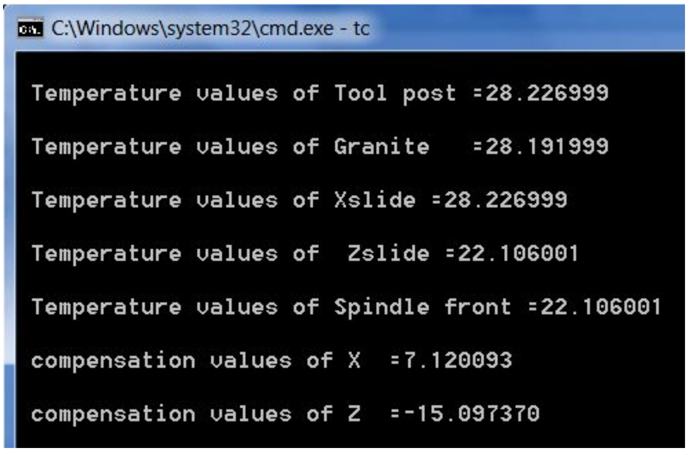
Epoch:	0	1200 iterations	1200
Time:		0:30:12	
Performance:	1.56e+03	0.00741	1.00e-05
Gradient:	5.48e+03	0.0190	1.00e-05
Mu:	0.0100	0.100	1.00e+10
Validation Checks:	0	482	1000

(plotperform)
(plottrainstate)
(plotregression)
Plot Interval: 1 epochs
✓ Opening Performance Plot

Fig. 13. (a) Performance plot; (b) Regression plot.(c) Neural network training

5.5. Real-time 'C' Programming for network calculations:

Key parameters (weights & Biases) have been extracted from the neural networks. 'C' programme has been developed for the neural network equations with weights & biases. This programme has been tested with the known temperatures and known distortions as shown below fig .14.



```
Temperature values of Tool post =28.226999

Temperature values of Granite   =28.191999

Temperature values of Xslide =28.226999

Temperature values of  Zslide =22.106001

Temperature values of Spindle front =22.106001

compensation values of X  =7.120093

compensation values of Z  =-15.097370
```

Fig14: 'C' Programme output with inputs & outputs

5.6. Interfacing with the open Architecture CNC controller:

- In real-time thermal error compensation, temperatures are acquiring in real-time, the 'C' programme computes the thermal deformation error and the errors are compensating through position offset or tool offset. Based on the controller/user requirement either by position offset or tool offset can be taken.
- The surface mountable temperature sensors (RTD) have been connected to Ndrive HLe 20-40, data logging in A3200 CNC controller. The temperature sensors offsets have been corrected with calibrated temperature sensor.

The thermal error compensation application module has been developed, runs in real-time run-silent mode, compensation takes place without intervention of CNC operator. This compensation module works only for multi tasking controllers.

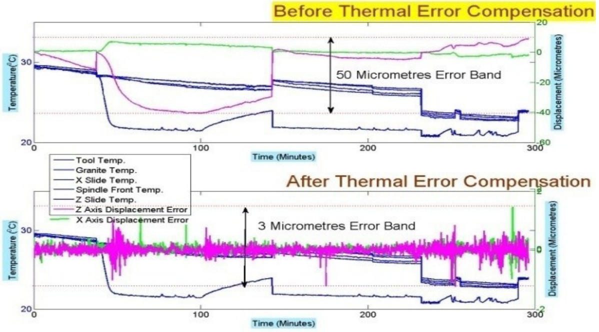


Fig15: Plot shows before and after thermal error compensation

6. Conclusion

The real-time thermal error compensation module has been successfully integrated to intelligent Ultra Precision Turning Machine (iUPTM) for compensation of X & Z thermal deformation errors. This real-time module take temperatures as inputs, computes the thermal error and compensation applies in real-time either by Tool offset (G54 Command) or Position offset command.

The complete methodology for experimentation, analytical modelling using Neural Networks, real-time extraction of key parameters, 'C' Programming for CNC interface, thermal error compensation application has been established. The same methodology can be applied for different environmental conditions and other CNC machines. Using this methodology the thermo mechanical deformation errors has brought down from 50 µm to 3 µm as shown in fig.15.

7. Future Work

The developed algorithm works well for the temperature range available in the experimental data collection. The present work is limited to one particular condition, because of the experimental setup limitation. Ideally the thermal experimentation needs to be carried out in a single time for all machining conditions.

8. Acknowledgements

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