A novel Approach for Thermal Error Modeling in CNC Turning Centre

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Abstract-- In CNC machine tools, transient temperature variation in the headstock assembly and ball screw system are the major contributors for spindle thermal error. A high-speed ball screw system naturally generates more heat and results in greater thermal expansion, adversely affecting the accuracy of positioning. Consequently, the present study focuses on the development of new thermal error model, to reduce the thermal error in spindle lateral direction (X-Component of the spindle). The proposed novel approach is based on the development of a net thermal error model by the integration of individual error models developed for the headstock assembly and ball screw system. The individual models are developed using multi linear ridge regression technique. The contribution of each heat source on net thermal error is evaluated by the use of net thermal error and the mean thermal error. The developed net thermal error model is validated to examine the accuracy and robustness under different experimental conditions. From the performance analysis of developed model, it has better accuracy and robustness and hence it can be used effectively for real-time thermal error compensation in CNC machine tools.

Index Term-- CNC Machine tools-Thermal error-Headstock assembly-Ball screw system-Ridge regression-Net thermal error, tool centre point (TCP).

I INTRODUCTION
The demand for high-speed/high-precision machine tools is rapidly increasing in response to the development of production technology that requires highly precise parts and high productivity [1]. The machine tool accuracy is greatly affected by thermo-elastic behaviour of the machine elements produced due to transient temperature variation and it lead to geometrical inaccuracies on the work-piece. Thermal influences are typically the major cause of thermo-elastic behaviour of machine elements and prominently contribute to the overall geometrical inaccuracy of the work piece [2]. Thermal errors of a machine tool arise from six main sources [3] namely: heat produced in the cutting process, change of room temperature, head-stock assembly, feed drives etc., and the minimization of the thermal errors of machine tools is concentrated on the following three aspects [4].

- Design of a thermally robust structure
- Compensation of thermal deformation
- Reduction in the heat sources

Among the above solutions, the reduction in heat sources is not possible beyond a certain limit as friction between parts in motion would certainly generate some heat. The design of thermally robust structure has a limit to the accuracy that could be achieved. Errors like thermal and cutting force deformation cannot be completely accounted for in design. It is usually time consuming and costly and it often ends in over design of machine structure. The use of alternative materials for machine tool applications is popular amongst machine tool builders, but these methods are still incapable of catering to changes that take place in the shop floor environment on a day to day basis. Compensation after thermal deformation gains success these days both on account of its of implementation as well as its cost-effectiveness [3].

The thermal error model forms one of the most critical elements in compensating for errors generated in machine tools on account of the temperature rise of the various machine tool elements. From the review of literature [4-12], it is found that the researchers have developed thermal error models by considering the thermal error at TCP (Tool Center Point) due to the combined displacement of spindle and the ball screw. The above error models contain terms which involve the temperature rise at salient points of the complete machine tool. It is proposed in the present work to determine the spindle thermal error due to the temperature rise in the headstock assembly and the X-axis error due to the temperature rise in the ball screw system separately followed by the estimation of net thermal error at TCP. The above approach has the advantage of retaining the physics of thermal expansion that is encountered in the headstock assembly and the ball screw system independently and finally determining the net error as an algebraic sum of the individual errors.

One of the major causes of thermal errors in linear axes is the heat generated in ball screw during operation at high speed. The area under discussion of this paper is to study the effects of ball screw system and head stock assembly on the accuracy
of machine tool to develop the thermal error model for head stock assembly and ball screw system separately and tried to control the thermal environment of the ball screw system to prevent flow of heat flux into workspace because in machine tools, the thermal error of the ball screw produces a position error directly. The methodology adopted in the present work is depicted in Fig.1.

The sensor points for temperature measurement were selected by accounting for the key heat sources in the 2-axis slant bed CNC turning center which have considerable influence on the thermal error. [7]. The locations for temperature measurement include the spindle bearings, chucking cylinder, ball screw motor and bearings. The temperature sensors (PT100) were attached to the structure by heat flow paste and are insulated from the environment by foam. The details of the temperature points and their positions are shown in Fig 4.

II MEASUREMENT OF TEMPERATURE AND THERMAL DEFORMATION

2.1 Experimental plan

In order to investigate the thermal behavior of the CNC turning centre, the temperature points were selected by accounting for all the heat sources in the turning centre. The major heat sources in the headstock assembly constitute spindle bearings and the chucking cylinder while the heat sources for the ball screw system include drive motor, ball screw and nut and support bearings.

Two typical load cycles one for spindle and the other for ball screw are considered as shown in Figures 2 and 3 respectively. The selected load cycles are of fluctuating types which are formulated based on the operations performed on the machine tool.
\( T_1 = \) Chucking Cylinder  
\( T_2 = \) Hydraulic pack of Chucking Cylinder  
\( T_3 = \) Spindle Motor  
\( T_4 = \) Spindle rear bearing  
\( T_5 = \) Spindle front bearing  
\( T_6 = \) Lubricant cover of the spindle  
\( T_7 = \) Headstock Temperature  
\( T_8 = \) Bed underneath the spindle  
\( T_9 = \) Hydraulic pack, machine side  
\( T_{10} = \) Coolant input close to the spindle  
\( T_{11} = \) Bed close to the transformer  
\( T_{12} = \) Bracket of the transformer  
\( T_{13} = \) Bearing of the spindle motor  
\( T_{14} = \) Ball Screw support bearing  
\( T_{15} = \) X-axis ball screw and nut

### Table 1

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>Related heat sources</th>
<th>Location of measurement probe and sensor holder</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Headstock Assembly</td>
<td>Probe on spindle and sensor holder on turret head</td>
</tr>
<tr>
<td>II</td>
<td>X-axis Ball Screw System</td>
<td>Probe on turret head (TCP) and sensor holder on spindle</td>
</tr>
<tr>
<td>III</td>
<td>Full machine tool</td>
<td>Probe on spindle and sensor holder on turret head</td>
</tr>
</tbody>
</table>

The setup for thermal error measurement is indicated in Table 1 using Marphoss’s LVDT sensor. The measurement probe constitutes a hardened steel rod mounted on the spindle nose. The purpose of using hardened steel is that the material has low coefficient of thermal expansion and does not deform on its own thereby indicating the actual deformation of the spindle.

In the first phase of experiments, spindle error due to deformation of headstock assembly is measured with respect to TCP by mounting the measurement probe on the spindle and sensor holder on turret head as shown in Fig. 5. The LVDT probe is attached to the tool turret and it measures the deflection of the probe at a distance of 30 mm from the chuck face. The temperature measurement in headstock assembly is made by operating the spindle and keeping the motor of the ball screw switched off.

In the second phase, X-axis error owing to temperature rise in the ball screw system is measured as given in Table 1. The spindle motor and the chucking cylinder were switched off during X-axis movement. Phase III refers to the experiment carried out for combined operation of both spindle and ball screw.

### 2.2 Variation of temperature and deformation

The transient variation of temperature in the headstock assembly and ball screw system are shown in figures 6, 7, 8 and 9 respectively. The corresponding variation for thermal error in X-direction for both is shown in Fig. 10.
In the headstock assembly, the thermal sensor attached to the chucking cylinder records a maximum temperature of 64°C while front spindle bearing records 37°C. When the spindle is suddenly stopped for a period from 4th hour to 6th hour and from 9th hour to 14th hour, the temperature falls significantly showing the sensitivity of the machine tool for internal heat generation. It is observed from the above figures that the variation of temperature as well as the thermal error is in accordance with the pattern of the load cycle.

In X-axis ball screw system, the heat caused by the drive motor and support bearings flows into the ball screw resulting in the temperature variation shown in Fig.9. The sensor attached to the ball screw and nut records a maximum temperature of 36°C. The consequence is an elongation of ball screw and a decreasing distance between TCP and the probe causing error in X-direction. The experimental data on temperature and thermal error have been used to develop the thermal error model.

III DEVELOPMENT OF THERMAL ERROR MODEL
From the measured data, thermal error models are developed for headstock assembly and ball screw system separately through the use of ridge regression technique and using these models, net thermal error is obtained. The mean error values are used to evaluate the contribution of headstock assembly and ball screw system on the overall thermal error.

The thermal error model describes the relationship between transient temperature variation and thermal errors [11]. A Multi linear regression is a statistical technique that uses several explanatory variables to predict the response variable; it derives a thermo-elastic relationship between multi-temperature variables and thermal error. The temperature variation is independent variable and thermal error as dependent variable to establish the thermal error model using regression.

The linear thermal error model will be of the form

\[ \delta = \beta_1 T_1 + \beta_2 T_2 + \beta_3 T_3 + \cdots + \beta_n T_n + \epsilon \]  

In present study, ridge regression technique is used for developing the thermal error model for headstock assembly and ball screw system. The above method is adopted owing to its merits explained below.

In multiple regression problems, the regressor variables (temperature variations) are intercorrelated. The situations where this intercorrelation is very large, there exists multicollinearity. It can have serious effects on the estimates of the regression coefficients in ordinary least-squares method. Several methods have been suggested in order to overcome the multi-collinearity problem. Ridge regression is one of method, which is an alternative method to ordinary least squares, it estimates the regression co-efficients by adding a degree of bias in order to reduce the standard errors. Ridge regression proceeds by adding a small value, k, to the diagonal elements of the correlation matrix [7].
\[ \beta = (T^\top T + kI)^{-1}T^\top \delta \]  \hspace{1cm} (2)

The covariance matrix is given by

\[ V(\beta) = (T^\top T + kI)^{-1}T^\top T(T^\top T + kI)^{-1} \]  \hspace{1cm} (3)

where \( k \) is the ridge parameter and \( I \) is the identity matrix. Small positive values of \( k \) improve the conditioning of the problem and reduce the variance of the estimates. Ridge tracing is used to choose an appropriate value of \( k \).

### 3.1 Thermal Error Model for headstock assembly

Fuzzy clustering analysis and regression analysis are carried out to identify the more significant temperature points in headstock assembly from the 13 thermal key points.

#### 3.1.1 Fussy Clustering Analysis

Fuzzy clustering method is based on fuzzy matrix to classify all of the research objects; the objects in the same cluster are very similar, while objects in different clusters have large dissimilarity [11].

Assumed Domain \( T = [T_1 \ T_2 \ T_3 \ \ldots \ T_n] \)

\( T_1, T_2, T_3, \ldots T_n \) represents input thermal sensors data. In order to classify \( T \), it is necessary to calculate the correlation coefficient \( r_{ij} \) of the statistics relationship between objects which are classified and then determine the fuzzy matrix.

When data of \( T_{ij} \) has all been standardized, the degree of similarity between samples \([T_{i1} \ T_{i2} \ T_{i3} \ \ldots \ T_{in}] \) and \([T_{j1} \ T_{j2} \ T_{j3} \ \ldots \ T_{jn}] \) can be determined through the method of multivariate analysis and therefore the fuzzy similar matrix \( R = [r_{ij}]_{n \times n} \) can be built.

\[
R = \begin{bmatrix}
  r_{11} & \ldots & r_{1n} \\
  \vdots & \ddots & \vdots \\
  r_{n1} & \ldots & r_{nn}
\end{bmatrix}
\]

Correlation coefficient is calculated using the following formula for \( k \)th measurement value of \( T_{ij} \) [12].

\[
r_{ij} = \frac{\sum_{k=1}^{n} T_{ik} \cdot T_{jk} - \bar{T}_i \cdot \bar{T}_j}{\sqrt{(\bar{T}_i - \bar{T})^2 + (\bar{T}_j - \bar{T})^2}}, \quad i=0,1,2, \ldots N
\]

where

\[
\bar{T}_i = \frac{1}{n} \sum_{k=1}^{n} T_{ik}
\]

\[
\bar{T}_j = \frac{1}{n} \sum_{k=1}^{n} T_{jk}
\]

Fuzzy equivalent matrix is calculated by the transitive closure of similarity by obtaining the square of \( R \), that’s \( R^* \) \( R = R^2 \), then \( R^2 \) \( R^2 = R^4 \), so on and so until we come to \( R^k \) \( R^k \), and \( R^k \) is the fuzzy equivalent matrix. The equivalent fuzzy matrix for the 13 temperature key points is given below.

\[
R = \begin{bmatrix}
0 & 0.956 & 0.956 & 0.999 & 0.919 & 0.939 & 0.958 & 0.951 & 0.764 & 0.959 & 0.643 & 0.631 & 0.809 \\
0.956 & 1 & 0.934 & 0.935 & 0.937 & 0.939 & 0.958 & 0.951 & 0.764 & 0.959 & 0.643 & 0.631 & 0.809 \\
0.956 & 0.929 & 1 & 0.934 & 0.935 & 0.937 & 0.939 & 0.958 & 0.951 & 0.764 & 0.959 & 0.643 & 0.631 \\
0.999 & 0.935 & 0.934 & 1 & 0.995 & 0.995 & 0.995 & 0.995 & 0.995 & 1 & 0.994 & 0.995 & 0.995 \\
0.919 & 0.937 & 0.935 & 0.995 & 1 & 1 & 0.996 & 0.984 & 0.733 & 0.969 & 0.954 & 0.601 & 0.639 \\
0.939 & 0.937 & 0.935 & 0.995 & 1 & 1 & 0.994 & 0.995 & 0.973 & 0.971 & 0.594 & 0.601 & 0.84 \\
0.958 & 0.899 & 0.981 & 0.900 & 0.986 & 0.994 & 1 & 1 & 0.684 & 0.967 & 0.538 & 0.659 & 0.759 \\
0.764 & 0.736 & 0.705 & 0.724 & 0.733 & 0.733 & 0.684 & 0.677 & 1 & 0.73 & 0.918 & 0.687 & 0.753 \\
0.959 & 0.936 & 0.935 & 0.968 & 0.969 & 0.971 & 0.967 & 0.959 & 0.73 & 1 & 0.389 & 0.614 & 0.833 \\
0.643 & 0.694 & 0.659 & 0.594 & 0.594 & 0.594 & 0.53 & 0.53 & 0.918 & 0.918 & 1 & 0.613 & 0.774 \\
0.631 & 0.634 & 0.614 & 0.629 & 0.601 & 0.601 & 0.659 & 0.662 & 0.67 & 0.614 & 0.613 & 1 & 0.623 \\
0.869 & 0.935 & 0.824 & 0.824 & 0.839 & 0.84 & 0.759 & 0.748 & 0.753 & 0.833 & 0.774 & 0.623 & 1
\end{bmatrix}
\]

The thirteen thermal sensors can be categorized into different groups with \( \lambda = 0.98 \) as given below.

<table>
<thead>
<tr>
<th>Group I</th>
<th>Group II</th>
</tr>
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<tbody>
<tr>
<td>Temperature Key points</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>0.967</td>
</tr>
<tr>
<td>( T_5 )</td>
<td>0.951</td>
</tr>
<tr>
<td>( T_6 )</td>
<td>0.948</td>
</tr>
<tr>
<td>( T_7 )</td>
<td>0.962</td>
</tr>
<tr>
<td>( T_8 )</td>
<td>0.945</td>
</tr>
<tr>
<td>( T_{4,5,7} )</td>
<td>0.979</td>
</tr>
<tr>
<td>( T_{4,5,6} )</td>
<td>0.974</td>
</tr>
<tr>
<td>( T_{4,5,8} )</td>
<td>0.975</td>
</tr>
</tbody>
</table>

From the fuzzy clustering analysis, \( T_4, T_5, T_6, T_7 \) and \( T_8 \) are classified as group I and \( T_1, T_2, T_3, T_9, T_{10}, T_{11}, T_{12} \) and \( T_{13} \) are classified as group II. Regression analysis is carried out for both the groups obtained from the fuzzy clustering analysis to determine the correlation between the thermal key points and thermal error as shown in Table II.

<table>
<thead>
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<td>0.975</td>
</tr>
</tbody>
</table>

Considering Group II, the thermal key points do not exhibit a strong relation with thermal error as compared to group I. Considering Group I, it is inferred that the combination \( T_1 T_2 T_7 \) has the highest correlation with thermal error as compared to \( T_4 T_5 T_6 \) and \( T_4 T_5 T_8 \). Finally, the three thermal key points \( T_4, T_5 \) and \( T_7 \) are selected for determining the thermal error (\( \delta T_h \)) in lateral direction (X-component) of the spindle in the headstock assembly.
\[(\delta_x)_h = 64.714 - 1.9504 T_4 - 1.2251 T_5 + 0.4315 T_7 \] (4)

\[(\delta_x)_h = 64.714 - 1.9504 T_4 - 1.2251 T_5 + 0.4315 T_7 - 0.4946T_{14} - 0.8864T_{15} \] (6)

where \((\delta_x)_h=(\delta_x)_b- (\delta_x)_0\)

The mean spindle thermal error for headstock assembly and the mean error for ball screw system are found to be 14.8144 \(\mu\)m and 6.97\(\mu\)m respectively.

**IV NET THERMAL ERROR**

The net thermal error model using the proposed approach is given by

\[(\delta_x) = 64.714 - 1.9504 T_4 - 1.2251 T_5 + 0.4315 T_7 - 0.4946T_{14} - 0.8864T_{15} \] (6)

where \((\delta_x)_h=(\delta_x)_b- (\delta_x)_0\)

The mean spindle thermal error for headstock assembly and the mean error for ball screw system are found to be 14.8144 \(\mu\)m and 6.97\(\mu\)m respectively.

**4.1 Model accuracy**

A comparison between the measured error and the predicted error based on the net error model is depicted in Fig.14 where the residual error is very minimal.

The performance of the above model was tested using experimental data obtained for a different combined load cycle and the results are shown in Fig.15.
4.2 Model Robustness

Accuracy means that the predicted value is almost closer to the actual value [13]. A model is said to have better robustness when it is applied for other experimental conditions, the model still has a satisfactory performance of prediction. A model with high robustness is more preferable than the model with high accuracy, because it can compensate.

The net thermal model is found to have a standard deviation of 0.698 µm and a predictive accuracy of 95.68% and hence the model has better prediction accuracy and robustness.

V CONCLUSION

The transient variation of temperature and thermal error in the headstock assembly and ball screw system of CNC turning centre have been investigated through experimentation. Individual thermal error models are developed for headstock assembly and x-ball screw system using ridge regression statistical approach. These models are integrated to develop the net thermal error model which combines the effect of the heat sources in the headstock assembly and the ball screw system. The spindle thermal error due to internal heat generation in headstock assembly is found to have the highest contribution of 68% while the shift of TCP due to the thermal elongation of X-axis ball screw amounts to 32% of net thermal error. The developed net thermal error model is validated by confirmation test and the results show that it has better fitting accuracy and robustness. The proposed error model has the attributes of being simple in structure with minimum number of key points and complying with the physics of the problem. Hence, the error model could be reliably used for the real-time thermal error compensation in CNC machine tools.

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