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Thermal error modelling of a three axes vertical milling machine using Finite element analysis (FEA)

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Abstract
The errors caused by thermal deformation directly affect the precision of a machine tool. Temperature changes of machine tool structures occur as a result of two reasons: firstly, internal heat sources like belt drives, motors and bearings. Secondly, external heat sources such as ambient temperature change of the work shop. These changes in machine tool structure temperature cause the heat to flow and because of this the machine tool element deforms.

Objectives
- Measuring temperature gradient and displacement of machine tool structures
- Creating a FEA Model and simulating the temperature and displacement of machine tools
- Comparing the experiment and simulated data

Methodology

Experiment: the experiment set up divided into two parts
1- Thermal imaging camera set up

End of heating cycle

Thermal imaging camera set up and a thermal image at end heating cycle

2- Non-Contact displacement Transducer Sensors (NCDT)

NCDTs use a magnetic field to sense the target

Creating FEA model and simulating it

Heat transfer conditions
- Heat transfer by Conduction: \( Q = KA(\frac{dT}{dx}) \)
- Heat transfer by Convection: \( Q = hA(T - T_a) \)
- Heat transfer by Radiation: \( Q = \varepsilon \sigma A(T^4 - T_a^4) \)

Where \( Q \) heat rate (W), \( K \) (W/m\(^\circ\)C) thermal conductivity, \( dx \) length (m), \( A \) temperature difference (\(^\circ\)C), \( T \) surface temperature (\(^\circ\)C), \( \varepsilon \) the Stefan Boltzmann Constant (W/m\(^2\)\(^\circ\)C\(^4\)), \( h \) heat transfer coefficient, \( T_a \) ambient temperature.

Results

Heat power (Non linear heat source relationship)

Machine structure temperature gradient

Machine structure deformation

Model simulation
The FEA was carried out using Dassault Systemes Simulation (Part of the Solidworks suite of software) to predict the temperature gradient and the spindle thermal deformation.

Correlation coefficients (R)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Conclusion
The accurate simulations can be used to predict errors under different operating conditions and to develop compensation models. Thermal error could be reduced to just 4 \( \mu \)m in the Z and Y axis directions from 35 and 20 \( \mu \)m respectively.