The Modelling of a Machine Tool
with Thermally Induced Displacements

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Modal Multifield Approach

**Displacement Modes:**

\[ u = \Phi_u z_u \]

\[ \epsilon = (\nabla_u \Phi_u) z_u = B_u z_u \]

\[ K_{uu} = \int B_u^T H_c B_u \, dV \]

**Thermal Modes:**

\[ \vartheta = \Phi_{\vartheta} z_{\vartheta} \]

\[ K_{u\vartheta} = \int B_u^T H_{\lambda} \Phi_{\vartheta} \, dV \]

\[ M_{uu} \ddot{z}_u + K_{uu} z_u = h_u + K_{u\vartheta} z_{\vartheta} \]
Thermal Response Modes

Heat Flow Analysis

Mechanical Analysis

FEM

\[ \Phi_\vartheta = [\ldots \vartheta_i \ldots] \]

\[ f_i = f(\vartheta_i) \]

\[ u_i = K_{uw}^{-1} \cdot f_i \]

\[ K_{uw} = [\ldots f_i \ldots] \]

\[ \Phi_u = [\ldots u_i \ldots] \]

Modal Reduction

Thermal Force Element

Extended Equations of Motion

MBS

RM-ER: Vehicle System Dynamics
Machine Tool: The Name of the Game

- Point-to-Point working task
- Drives with excellent dynamical properties for high performance!
- High accuracy demanded!
- Thermal loads caused by drives or working task
  - relevant displacements?
  - system-dynamical description?
  - CAE work flow?
Machine Tool: Kinematic Scenario

\[
\begin{align*}
\bar{q}(t) &= \bar{q}(t + nT) \\
\bar{y}(t) &= \bar{y}(t + nT) \\
n &\to \infty
\end{align*}
\]

\[\implies -\lambda \bar{y}_{yy} \approx q(y)\]
Machine Tool: Thermal Modes

2 steady state heat transfer FEM-solutions ⇒ 2 thermal modes ⇒ 2 thermal response modes
Machine Tool: Thermal Response Modes

Comparison FEM vs. MBS

Thermal response modes
FEM : MBS ≈ 1:1

Eigenvalue Analysis

- 90 Hz
- 105 Hz
- 114 Hz
- 384 Hz
- 387 Hz
- 391 Hz
- 1694 Hz
- 2368 Hz

Eigenmodes and thermal response modes were weakly coupled.
Machine Tool: Dynamic Simulation

TCP: tool center point
P2: reference point, moving along the machine base with predefined kinematics
$\Delta r_3$, $\Delta z_3$: reference displacements of TCP without thermal loads
Machine Tool: Conclusions

- Description and CAE workflow of thermal displacements is feasible.
- In general, modes are not orthogonal.
- High frequency modes are involved.

- What about transient temperatures?
  - Is Duhamel’s Assumption still valid?
    - If yes, thermal displacements could generally be provided as driven equilibrium solutions!
- What about more localised temperature peaks?
Outlook: Brake Disc

Load definitions are based on a midsize car at 90 km/h that stops, and are applied continuously in space and time.

Temperatures and axial displacements of a single hot spot after 2,199 s, obtained by FEM (reference solution).
Outlook: Brake Disc

Preliminary Results

Temperatures at Node 415 and Node 4519 (central to the hot spot on both surfaces of the disc)

Displacements of Node 20 (on the outer edge of the disc)

MMA: modal multifield approach