Open Loop Inertial Cross-Talk Compensation Based on Measurement Data

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Content

- Motivation
- What is Cross-Talk?
- Measurement
- Modeling
- Compensation Procedure
- Results and Conclusion
Motivation

Positioning 50 mm
Order of errors:
- 5 µm
  - Straightness
  - Hysteresis
- 50 µm
  - Cross-talk
What is Cross-Talk?

- **Standard ISO/TR 230-8**
  - inertial cross-talk

- **Effect**
  - Deviation orthogonal to the accelerated direction
  - $\ddot{X} \rightarrow \dot{EY}\ddot{X}, \dot{EZ}\ddot{X}$

- **Influences**
  - Stiffness $k$ in guideway
  - $Y$ offset (lateral) from point of force application and center of mass (CM) ($\Delta Y$)
  - $X$ offset from center of mass to the tool center point (TCP) ($\Delta X$)
  - Acceleration (actuator force $F_X$)
Mathematical Description of Cross-Talk?

- **Model**
  - $EY\ddot{X}$ Cross-talk
  - $\phi$ Proportional factor
  - $F_X$ Actuator force
  - $\Delta_Y$ $Y$ offset (lateral)
  - $\Delta_X$ $X$ offset
  - $k_{\text{Guideway}}$ Stiffness

- $EY\ddot{X} = \phi \cdot \frac{F_x \cdot \Delta_x \cdot \Delta_y}{k_{\text{Guideway}}}$
Cross-Talk Countermeasures

- Machine design
  - Drive in the center of gravity (DCG)
- Reduction of the dynamic parameters
- Compensation using numerical control (NC)
  1. Measurement of the cross-talk error
  2. Derivation of the cross-talk prediction model
  3. Compensation of the position set-point

Mori Seiki, NMV5000 DCG
Photo: Mori Seiki
Cross-Talk Measurement

- Cross-grid XY-measurement
  - 2D
  - Optical measurement system
  - Non-contact
  - Similar principle to an optical linear scale
- Cross-Grid measurement for different
  - Y offsets (lateral)
  - Accelerations
  - X offsets do not change
How to Model the Cross-Talk Effect
(Acceleration dependent for a given position)

- Orthogonal deviation $EY\ddot{X}$ is proportional to the acceleration $\ddot{X}$
- Linear fit of measurement data
- Exclude sections to improve the linear fit
  - Low accelerations: non-cross-talk deviations are dominant
  - Low orthogonal deviations: acceleration influenced by numerical effects
Position Dependence of Cross-Talk I

- Dependence of the Y-Position
  - Linear fitted proportionality factors

<table>
<thead>
<tr>
<th>Y-Position</th>
<th>EY\ddot{X}/\dddot{X} [\mu m/(m/s^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 mm</td>
<td>7.6</td>
</tr>
<tr>
<td>1200 mm</td>
<td>10.8</td>
</tr>
</tbody>
</table>

actuator force

center of mass

Y-position

side view

EY\ddot{X} (orthogonal deviation)
Position Dependence of Cross-Talk II

- Proportionality factor \( \text{EY}\ddot{X}/\ddot{X} \) for any \( Y_{TCP} \)

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</thead>
<tbody>
<tr>
<td>300 mm</td>
<td>7.6</td>
</tr>
<tr>
<td>( Y_{TCP} )</td>
<td>( \text{EY}\ddot{X}/\ddot{X} )</td>
</tr>
<tr>
<td>1200 mm</td>
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</tr>
</tbody>
</table>

- Model

\[
\text{EY}\ddot{X}(Y_{TCP}, \ddot{X}) = \phi \cdot \ddot{X} \cdot (Y_c \cdot m_c + (Y_{TCP} - Y_0) \cdot m)
= \ddot{X} \cdot (H_0 + H \cdot Y_{TCP})
\]

\( \phi \): proportional factor
Compensation Procedure for Cross-Talk Error

- Step 1: Measurement of the cross-talk error
- Step 2: Derivation of proportionality factors $E_Y \hat{X}/\hat{X}$
- Step 3: Compensation of the position set-point depending on the nominal acceleration and position

NC-Code

Open-Loop Control

Cross-Talk Compensation

Closed-Loop Control

Machine

$Y_{TCP}$
Limited Actuator Dynamics

- Direct compensation
  - Add model predicted cross-talk to the set-point position of Y
  - Incomplete compensation
- Reason
  - Actuator dynamics, low pass behavior of the drive
  - Modeling with a TP1 element
- Improved compensation
  - Scaling of the model predicted compensation values

\[
\begin{align*}
\text{Cross-talk} & \\
& -0.04 \quad -0.03 \quad -0.02 \quad -0.01 \quad 0 \quad 0.01 \quad 0.02 \quad 0.03 \quad 0.04
\end{align*}
\]

Position of accelerated axis X [mm]

Orthogonal deviation $EY_X$ [mm]

$Y_{setpoint}$ $K_p$ $TP1$ $\int$ $Y_{actual}$
Results and Conclusion

- Cross-talk reduction realized only by set-point modification
- Procedure can be used also with multi-dimensional movement
- Reduction of the orthogonal deviation of about 50% in experiment
Discussion

- Further reduction of cross-talk should be possible
- Model uncertainty is about ±20 µm
- To consider
  - Position control cycle time (4.5 ms)
  - Better inversion of the drive dynamics
  - Dynamics of the compensating axis
Influence of the Machine Dynamics

- Low machine excitation by the acceleration of the compensating axis
- Effects that cannot be compensated (vibrations e.g.)
Summary

Compensation Procedure

- Measurement of the dynamic orthogonal deviation (cross-talk) during a single axis positioning movement
- Determination of the proportionality factors between acceleration and orthogonal deviation
- Position dependent model of the cross-talk
- Compensation of the nominal position values

Improvement:

- The orthogonal deviation is reduced by 50% using the proposed compensation strategy.
Thank you for your Attention
Questions ?
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Inertial Cross-Talk Principle – ISO/TR 230-8

“displacements perpendicular to the intended direction of motion, owing to a lateral offset between the driving force and the center of mass, which lead to tilt motions during acceleration and deceleration”
Cross-Talk Principle I

driving force

center of gravity

rolling elements of guideway
Cross-Talk Principle II

- Driving force
- Rolling elements of guideway
- Center of gravity
- Cross-talk
Cross-Grid

1 reader
2 grid plate
www.heidenhain.com
KGM+

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ASPE 1999, Monterey California