Design and Analysis of Flexible Machining Fixtures

Jose F. Hurtado
Advisor: Shreyes N. Melkote
Precision Manufacturing Research Consortium
Georgia Institute of Technology
Atlanta, Georgia

October 18th, 2000
Background

- A flexible fixture accommodates parts with different shapes and sizes.

(U.S. Patent 4,936,560)  
(U.S. Patent 5,722,646)  
(Cutkosky et al., 1982)
Motivation

- Flexible fixtures of the mechanical type, such as the bed-of-nails, have been proposed for machining.

Matrix Pin-Array Type Machining Fixture (X-Clamp)
Objectives

- Develop a design methodology and analysis tools for mechanical flexible machining fixtures, e.g. pin-array.

- Specific areas of interest:
  - Fixture-Workpiece **conformability** and its effect on static **stability**.
  - Tolerance-based **stiffness** optimization of flexible (and dedicated) fixtures.
Fixture-Workpiece Conformability

• Development and experimental validation of global and local conformability metrics, $C_1$ and $C_2$

\[ C_1^{2D} = \frac{1}{\text{Perimeter}(\beta) - \text{Perimeter}(\text{SP})} \]

\[ C_1^{3D} = \frac{1}{\text{Surface Area}(\beta) - \text{Surface Area}(\text{SP})} \]

\[ C_2 = \sum_{i=1}^{N} \Delta_n A_i d_{ij} \quad (i = 1...N, j = 1...N) \]

\[ i \Delta_n = i \Delta_n^c + i \Delta_n^w \]
Development and validation of a model to quantify the static stability of the fixture-workpiece system accounting for all compliance sources.

- **Workpiece Surface Model**
- **Fixture Element Stiffness**
- **Workpiece F.E. Model**
- **Contact Mechanics Solutions**
- **Computes \([k_o]_{6 \times 6}\) (Howard and Kumar, 1994)**
- **Fixure-Workpiece Reaction Forces** (Numerical Minimization of Total Complementary Energy)
- **Min(eig(\(k_o\)))**
- **Static Stability Metric, \(S\)**
- **Principal Stiffness Directions, \(\sigma_i\)**
Application of the Conformability-Stability Model

- Computer simulations to study the effect of conformability on static stability of fixture-workpiece system.

- The model can be used for the optimal reconfiguration of flexible fixtures:
  - To determine the optimal orientation of the workpiece in the flexible fixture that maximizes stability and achieves a part feature accessibility goal.
Example #1. Computer Simulation.

Scenario #1

\[ S = 4510 \]
\[ C_1 = 4.3 \times 10^{-6} \text{ mm}^{-2} \]
\[ C_2 = 167.9 \text{ mm}^4 \]

Scenario #2

\[ S = 8240 \]
\[ C_1 = 8.9 \times 10^{-6} \text{ mm}^{-2} \]
\[ C_2 = 212.6 \text{ mm}^4 \]
Experimental Validation

- This model showed good agreement with experimental data taken from the X-Clamp flexible fixture.
Validation Results

![Diagram of layouts with mobile and fixed units]

![Bar charts showing validation results for different layouts]
Validation Results

![Diagram showing layouts and measurements]

### Layouts
- **A** and **B**: Mobile Unit
- **C** and **D**: Fixed Unit
- **Layout 1**
- **Layout 2**
- **Layout 3**

### Graph
- **Layout #**: 1, 2, 3
- **Measurements**:
  - **δ_exp**
  - **δ_pred**

### Table

<table>
<thead>
<tr>
<th>Layout</th>
<th>Mobile Unit</th>
<th>Fixed Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>1, 3, 4, 12</td>
<td>5, 6, 8</td>
</tr>
<tr>
<td>3</td>
<td>1, 3, 4, 5</td>
<td>6, 8</td>
</tr>
</tbody>
</table>

### Notes
- Validation Results
- δ = exp δ = pred
Tolerance-Based Stiffness Optimization

- Determine fixture stiffness necessary to keep within tolerance the workpiece feature error due to fixture elastic deformation.
### Example #2. Optimal Design.

<table>
<thead>
<tr>
<th>Array Parameters</th>
<th>EL1</th>
<th>EL2</th>
<th>EL3</th>
<th>EL4</th>
<th>EL5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch, ( P ) (mm)</td>
<td>4.33</td>
<td>6.71</td>
<td>4.25</td>
<td>4.24</td>
<td>4.24</td>
</tr>
<tr>
<td>Pin Radius, ( R ) (mm)</td>
<td>1.03</td>
<td>0.71</td>
<td>0.96</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Number of Columns, ( N_{COL} )</td>
<td>25</td>
<td>17</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Number of Rows, ( N_R )</td>
<td>26</td>
<td>17</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Axial Stiffness (N/mm)</td>
<td>1.20E+07</td>
<td>2.73E+06</td>
<td>1.09E+07</td>
<td>1.13E+07</td>
<td>1.12E+07</td>
</tr>
<tr>
<td>Bending Stiffness (N/mm)</td>
<td>1.31E+04</td>
<td>1.35E+03</td>
<td>1.02E+04</td>
<td>1.10E+04</td>
<td>1.08E+04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>EL6</th>
<th>EL7</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch, ( P ) (mm)</td>
<td>4.24</td>
<td>4.56</td>
<td>6.61</td>
<td>6.61</td>
<td>4.00</td>
</tr>
<tr>
<td>Pin Radius, ( R ) (mm)</td>
<td>0.97</td>
<td>1.01</td>
<td>0.85</td>
<td>0.86</td>
<td>1.29</td>
</tr>
<tr>
<td>Number of Columns, ( N_{COL} )</td>
<td>26</td>
<td>24</td>
<td>17</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>Number of Rows, ( N_R )</td>
<td>26</td>
<td>25</td>
<td>17</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td>Axial Stiffness (N/mm)</td>
<td>1.13E+07</td>
<td>1.07E+07</td>
<td>3.80E+06</td>
<td>3.83E+06</td>
<td>2.10E+07</td>
</tr>
<tr>
<td>Bending Stiffness (N/mm)</td>
<td>1.09E+04</td>
<td>1.11E+04</td>
<td>2.77E+03</td>
<td>2.82E+03</td>
<td>3.78E+04</td>
</tr>
</tbody>
</table>
Future Work

- Experimental validation of the tolerance-based stiffness optimization algorithm.

- Synthesis of pin-array type flexible machining fixtures.