Sensitivity analysis of forming process parameters regarding the shape accuracy of single and assembled parts

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Outline

1. Motivation

2. S-rail forming and joining process chain – sensitivity analysis and optimization

3. Results of the analysis of forming process parameters – sensitivity and RDO

4. Optimization of framing station parameters

5. Enhancement of the optimization possibilities using SOS

6. Summary and Outlook
1. Motivation

Analysis of the shape accuracy of single and assembled parts

Analyzing the dimensional accuracy of process chains

**Aim:** Shortening of product development cycles and prediction of the dimensional accuracy at an early product development stage

→ Simulative investigations instead of an hardware phase

Evaluation in an optical measurement system

- X, Y, Z-Displacement
- Sheet Thickness

Evaluation parameters dimensional accuracy

Forming

Mechanical Joining

Z-distance to reference design in mm

-2 0 +2

Dimensional accuracy after different process chain steps
2. S-rail forming and joining process chain
Analysis of the sensitivity of forming (and joining) parameters

- **Blank thickness** $t_{\text{blank}}$: 0.95 – 1.05 mm
- **Blank translation** $(x/y\text{vers})$: -10 to 10 mm
- **Blankholder forces** $b_{\text{f4}}$: 30 kN – 150 kN

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**Clamps**: X, Y- und Z-position of the 6 clamps

**Clinching points**: X- and Y-position

**Start Design = Best Design**

**Best Design** $x/y\text{vers} = -9.5$ mm

Sensitivity analysis of the joining conditions
Sensitivity analysis of the clamping conditions

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3. Results of the analysis of forming parameters
OptisLang results - Linear correlation matrix

The influence of y-translation has a comparatively higher influence on the OBJ_Y (-0.873) compared to its influence on the OBJ_Z (0.641).

Blankholder force (bf4) and the friction coefficient ($\mu$ left out for the Robust Design Optimization).

Definition of the objectives:

$\text{OBJ}_x$ : value of all nodes' displacement in x-direction

$\text{OBJ}_y$ : value of all nodes' displacement in y-direction

$\text{OBJ}_z$ : value of all nodes' displacement in z-direction

Value = Mean value x standard deviation
3. Results of the analysis of forming parameters
OptisLang results– Global Sensitivities and metamodel

- Y-Translation in reference to its initial plate position with highest influence on x-, y- and z-displacement
- 89% of the parameter influence on the nodal displacements dedicated by three control / noise variables

Y-Translation in reference to its initial plate position with highest influence on x-, y- and z-displacement

89% of the parameter influence on the nodal displacements dedicated by three control / noise variables
3. Results of the analysis of forming parameters

Comparison of simulation and experiments

Deviation between simulation and experiment:

<table>
<thead>
<tr>
<th>Material</th>
<th>AA 6014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape:</td>
<td>S-Form (A)</td>
</tr>
<tr>
<td>Thickness outer part:</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Blankholder force:</td>
<td>90 kN</td>
</tr>
<tr>
<td>Friction coefficient:</td>
<td>0.07</td>
</tr>
<tr>
<td>Blank translation (x,y):</td>
<td>0 mm</td>
</tr>
</tbody>
</table>

Initial blank x-y-positions:

- X=0; Y=0
- X=3; Y=0
- X=0; Y=3

Blankholder forces:

- 150 kN
- 90 kN
- 30 kN
4. Optimization of framing station parameters

Sensitivity analysis and optimization of framing station parameters

Model with parametrized clamps and joints:

- **Reference Design with deformed single parts**
- **Validator Design**
- **Postprocessing Sensitivity analysis**
- **Postprocessing Optimization - EA**
- **Postprocessing Validator System**

Clamps, ε [-5;5] with i = 1..6

Reference Design with nominal single parts

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4. Optimization of framing station parameters

Sensitivity results of z-positions of the clamps

Varied parameter space:

Six z-positions of the clamps ( # CP = clamping sequence)

Linear correlation matrix:

Metamodel - CoP:

<table>
<thead>
<tr>
<th></th>
<th>CP1</th>
<th>CP2</th>
<th>CP3</th>
<th>CP4</th>
<th>CP5</th>
<th>CP6</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer part</td>
<td>7.6</td>
<td>9.0</td>
<td>37.5</td>
<td>36.5</td>
<td>21.4</td>
<td>34.4</td>
<td>84.6</td>
</tr>
<tr>
<td>Inner part</td>
<td>0</td>
<td>4.5</td>
<td>28.6</td>
<td>21.6</td>
<td>26.8</td>
<td>32.3</td>
<td>82.9</td>
</tr>
</tbody>
</table>

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4. Optimization of framing station parameters

Optimization objectives and results

Objectives (according to the Euclidian Norm:)

Objective scalar value \( a = \min \frac{1}{\dim(R^n)} \sqrt{\left( \left( \begin{array}{c} \text{node 1}_z \\ \text{node 2}_z \\ \text{node i}_z \end{array} \right) + \left( \begin{array}{c} \text{u 1}_z \\ \text{u 2}_z \\ \text{u i}_z \end{array} \right) - \left( \begin{array}{c} \text{node 1}^*_z \\ \text{node 2}^*_z \\ \text{node i}^*_z \end{array} \right) \right)^2} \)

Optimization strategies:

- Evolutionary algorithm for minimizing \( a \) for the whole outer part (OP) (“OP all”)
- Evolutionary algorithm for minimizing \( a \) for the right and left flanges of the outer part (“OP right-left”)

Optimization results

<table>
<thead>
<tr>
<th>Reference</th>
<th>EA - “Outer part all“</th>
<th>EA -“Outer part right-left”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notation</td>
<td>Z-value [mm]</td>
<td></td>
</tr>
<tr>
<td>CP1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CP2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CP3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CP4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CP5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CP6</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Anchors:
\( \text{node 1}_z \): z-Coordinate joining deformed meshes
\( \text{u 1}_z \): z-displacement of the node
\( \text{node 1}^*_z \): z-Coordinate joining nominal meshes
5. Enhancement of the optimization possibilities using SoS – Random Field Model

Approximation of a random design with

- mean value + standard deviation of the nodes’ displacement \((x, y, z\) and normal direction)\)
- linear combination of deterministic “scatter shapes” multiplied with random coefficients (“amplitudes”)

\[ \text{perturbed geometry} \approx \mu + \phi_1 \cdot z_1 + \phi_2 \cdot z_2 + \phi_3 \cdot z_3 + \phi_4 \cdot z_4 + \ldots \]

Accurately resembles

- Statistical moments (mean, standard deviation…)
- Spatial correlations (anisotropic, inhomogeneous…)

Use in optimization: Representation of field variations as found in DoE; Combination with MOP to approximate field variations based on input parameters
5. Enhancement of the optimization possibilities using SoS – Process flow

Influencing factors of a framing station on the shape accuracy

Tobias Konrad
06/11/2015

6 deformed meshes (.stl)
1 nominal mesh/assembly (.stl)

Six z-positions of clamps [-3, 3]

Generation of shapes
Statistical moments

Coordinate deviation in normal direction

Variation (cumulative)
5. Enhancement of the optimization possibilities using SoS – Results

Evaluation possibilities:

[ Check plausibility of random field model ]

1) Accuracy of CAE process (a priori)
   Analyze how well the CAE process can resemble the target solution

2) Accuracy of F-MOP (a priori)
   Show F-CoP for whole model
   Show and rank F-CoP (sensitivity) of individual input parameters onto
different mesh locations

3) Accuracy of F-MOP solution (a posteriori)
   For coordinate deviation, compare prediction of F-MOP with true solution at
best design
5. Enhancement of the optimization possibilities using SoS – Results

0) Plausibility test of random field model: Check scatter shapes

Shape #1 (49%)

Shape #2 (24%)

Shape #3 (15%)

Shape #4 (7%)
5. Enhancement of the optimization possibilities using SoS – Results

1) Accuracy of CAE process (a priori)

- Analyze how well the CAE process can resemble the target solution
- Strategy: Analyze the variation shapes found in the DoE and check how well they can represent a zero deviation from the CAD0 geometry

Best possible solution of the CAE process (Z-axis)

Best possible solution:
- maximum positive deviation: 1.35 mm
- maximum negative deviation: -0.93 mm

But:
- corresponding random field amplitudes outside of DoE value range
- optimum expected to be worse
5. Enhancement of the optimization possibilities using SoS – Results

1) Accuracy of CAE process (a priori)

Correct amplitude values of zero design to amplitude bounds in DoE

This roughly approximates how well the CAE process can reproduce the target solution within the value bounds of the DoE

Best possible solution within DoE value bounds:

- maximum positive deviation: 1.41mm
- maximum negative deviation: -1.63mm
5. Enhancement of the optimization possibilities using SoS – Results

2) Accuracy of F-MOP (a priori)

F-CoP should be 90-100% at positions of interest, in particular in regions with large variation

May be less at locations that are not critical (e.g. at folds, corners or seams)

Ergo: suitable for optimization on field meta model
5. Enhancement of the optimization possibilities using SoS – Results

3) Accuracy of F-MOP solution (a posteriori)

Nominal geometry of the assembly (calculated)  
Verification run with best/optimized design in SoS

Comparison of coordinate deviation along z axis with respect to CAD0 geometry

Discussion: F-MOP underestimates deviation. Most input parameters at DoE value ranges

Changes: 1. Enhance DoE bounds, 2. Direct optimization

F-MOP  
-1.9 .. 2.05 mm

Abaqus  
-3.5 .. 2.1 mm
6. Summary and Outlook

**Summary**

- Y-translation of the S-rail plate with a higher influence on the dimensional accuracy compared to the x-translation in simulation and experiment
- Usage of metamodels of the sensitivity analysis (high accuracy) to reduce the calculation times of the Robust Design Optimization of **forming** and **framing station** parameters
- SOS as an enhancement or supplement (vector values / FMOP) \(\rightarrow\) FMOP approximates well qualitative distribution of geometric deviation

**Outlook**

- Automatic translation and rotation of sheets matching the target geometry
- Robustness analysis with SoS: Analyze influence and sensitivity of uncertain input parameters onto joining process
- **Uncertain**  
  a) clamp positions
  b) initial geometries resulting from deep drawing process