Single Point Incremental Forming using Adaptive Remeshing Technique with Solid-Shell Finite Elements


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Outline

1. Introduction

2. SPIF Numerical simulation

3. Adaptive Remeshing

4. Benchmark example
   4.1. Solid-Shell Element: RESS (Reduced Enhanced Solid-Shell)

5. Final Considerations
- Single point incremental forming (SPIF) is a sheet metal forming process that is appropriate for rapid prototyping.

- In SPIF, the lower surface of the metal sheet doesn’t require any dedicated dies or punches to form a complex shape.

![Diagram of SPIF process]

- The tool is guided by numerical control system, which defines the trajectory where the forming tool follows and progressively deforms a clamped sheet into its desired shape.

- The zone where high deformations occur is always close to the current location of the tool.
PROBLEM:

- The constantly changing contact between the tool and the metal sheet during the process.
- The nonlinearities involved causes a huge computational time.

The nonlinear finite element code used is the LAGAMINE developed in FORTRAN by MSM team of ArGENCo department in University of Liège since 80’s.

In LAGAMINE was developed the Adaptive Remeshing available only for Shell finite elements*.

The Adaptive Remeshing Technique was extended to use with 8 nodes solid element.

Objective:

- Use a 3D constitutive law
- Prediction of the sheet thickness strain
- Avoid the initial refined mesh with 8 nodes finite element

*see Cedric Lequesne et al., Numisheet 2008, Switzerland, September 1 - 5, 2008.
Remeshing Criterion

- Selection of a neighborhood around the position of the tool center

- Proximity condition:
  \[ D^2 \leq \alpha (L^2 + R^2) \]

- D: minimum distance between the tool center and the four nodes of the contact element
- L: length of the longest diagonal of the element
- R: radius of the tool
- \( \alpha \): coefficient adjusting the size of the neighborhood chosen by the user
Derefinement Criterion

- Computation of the initial relative position:
  \[ X_v = \sum_{i=1,4} H_i(\xi, \eta)X_i \]

- Computation of the distance
  \[ d = |X_c - X_v| \]

- Criterion of reaction of coarse element
  \[ d \leq d_{\text{max}} \]

- \( H_i \): interpolation function
- \( x, h \): initial relative positions of the node in the coarse element
- \( X_i \): nodes positions of the coarse element
- \( X_c \): Current position of the node
- \( d_{\text{max}} \): maximal admissible distance chosen by the user
Interpolation of state variables and stress

\[ Z_j = \begin{cases} 
\sum_k \frac{Z_k}{R_{kj}^n} + \frac{CZ_p}{R_{pj}^n} & \text{if } R_{pj} > R_{\min} \\
\sum_k \frac{1}{R_{kj}^n} + \frac{C}{R_{pj}^n} & \text{if } R_{pj} \leq R_{\min} \\
Z_p & \text{if } R_{pj} = R_{\min} 
\end{cases} \]

- **j**: is the index of the new integration point
- **k**: is the index of the integration point of another element
- **p**: is the index of the closest integration point
- **Zi**: can be the stress or variables of state components at the integration point j
- **Rkj**: distance between the integration point k and j

With:

- \( R_1 = 1.5d \)
- \( R_{\min} = 0.0001D \)

Adaptive Remeshing

- C: coefficient defined by the user
- n: degree of interpolation
- d: highest diagonal of the element
- D: highest diagonal of the structure
Adaptive Remeshing

Flowchart:

1. MESH WITH REMESHING (Next Steps)
2. INITIAL MESH (First Step)
3. LAMIN2
   - Check the convergence iteratively
4. ELEMB
   - Element's loop
5. ELEMENT SUBROUTINE
6. Integration points loop
7. ELEMB2
8. Converge?
   - NO
9. LAMIN2
10. Has remeshing elements?
    - NO
11. Write in output files
    - YES
12. REMESHING?
    - YES
13. ADAPT_REMESH
    - Generation of the new elements
14. PRINTER
    - ECRVAR
    - PRIDON
15. INTERPOL_ELEM
    - Interpolates the stress and state variable of coarse elements deactivated
16. INTERPOL_ELEM
    - Interpolation of the stress and state variables for new elements
Line test description

- Simple SPIF process:
  - Material: An aluminium alloy AA3003-O
  - Thickness: 1.2 mm
  - Spherical tool radius: 5 mm

- Boundary conditions:
Line test description

- Composed by 5 steps:
  1. Indentation of 5 mm
  2. Line movement at the same depth along the X axis
  3. Second indentation to the depth of 10 mm
  4. Line at the same depth along the X axis
  5. Unloading
Material

– Material: An aluminium alloy AA3003-O

– The constitutive law: Hill (Isotropic behaviour law)

– Parameters:
  
  Young modulus: $E_1 = E_2 = E_3 = 72600 \text{ MPa}$
  
  Poisson ratio: $\nu_1 = \nu_2 = \nu_3 = 0.36$
  
  Coulomb modulus: $G_1 = G_2 = G_3 = 26691.18 \text{ MPa}$
  
  Lankford coefficients defining the yield locus:
  $F = G = H = 1.0; N = L = M = 3.0$

– Hardening Swift law: $\sigma_{eq} = K (\varepsilon_0 + \varepsilon_{pl})^n$ with $K = 180.0$, $\varepsilon_0 = 0.00057$, $n = 0.229$
- 4 types of Elements:
  - 8 node solid-shell finite element RESS with 3GP
  - Contact element CFI3D with 4GP
  - Shell element COQJ4 with 4GP
  - Contact element CLCOQ
- 2 types of mesh:
  - Coarse with 72x2 elements with one element in thickness direction (RESS+CFI3D)
  - Coarse with 72 elements COQJ4
  - Reference without remeshing 806X2 elements (RESS+CFI3D)
RESS (Reduced Enhanced Solid Shell)*

- Solid-Shell Element specially design to use in metal forming applications
- Implemented in LAGAMINE code
- Integration scheme (a) advantages:
  - Reduced integration in plane
  - Arbitrary number of integration points in one single layer in thickness direction
- Combination between displacement strain and enhanced strain components interpolated by enhanced matrix with only enhanced mode
- Stabilization technique

Evolution of tool during the line test with RESS

![Graph showing force over time with different remeshing configurations.

- Blue line: RESS with remeshing n=3
- Yellow line: RESS with remeshing n=1
- Orange line: RESS with remeshing n=2
- Gray line: Reference (without remeshing)
Shape in a cross-section

Numerical results

-10 -8 -6 -4 -2 0 2 0 20 40 60 80 100 120 140 160 180

x [mm]
y [mm]

N=1 N=2 N=3 Reference (without remeshing)
Numerical validation

- Comparison between experimental and numerical results:

- Divisions per edge \((n)\): 3 nodes (one element is divided by 16 new elements)
Final mesh using adaptive remeshing

Initial $\rightarrow$ 1st step $\rightarrow$ 2nd step
## Comparisons of time performance

<table>
<thead>
<tr>
<th>Reference</th>
<th>COQJ4 4GP</th>
<th>RESS 3GP</th>
<th>Classic 8GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU time</td>
<td>5m 36s</td>
<td>18m 54s</td>
<td>17m 9s</td>
</tr>
<tr>
<td>Nº of Iterations</td>
<td>2859</td>
<td>1194</td>
<td>1107</td>
</tr>
<tr>
<td>Nº of steps</td>
<td>579</td>
<td>167</td>
<td>203</td>
</tr>
</tbody>
</table>

### N=1

| CPU time  | 1m 18s    | 2m 9s    | 1m 31s      |
| Nº of Iterations | 4164     | 907      | 725         |
| Nº of steps | 1041     | 153      | 158         |

### N=2

| CPU time  | 1m 13s    | 5m 4s    | 4m 7s       |
| Nº of Iterations | 2792     | 1059     | 680         |
| Nº of steps | 698      | 197      | 133         |

### N=3

| CPU time  | 1m 23s    | 6m 39s   | 5m 29s      |
| Nº of Iterations | 2076     | 1095     | 946         |
| Nº of steps | 519      | 163      | 170         |
Statistics results

• Total CPU time spent at the elements level:

<table>
<thead>
<tr>
<th></th>
<th>COQJ4</th>
<th>RESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element scheme</td>
<td>100%</td>
<td>89%</td>
</tr>
<tr>
<td>Contact elements</td>
<td>0%</td>
<td>11%</td>
</tr>
<tr>
<td>Constitutive law</td>
<td>24%</td>
<td>44%</td>
</tr>
</tbody>
</table>

• The CPU time spent with constitutive law corresponds to a 24% of the total time spent in the shell elements

• Using RESS the CPU time spent with constitutive law corresponds to a 44% of the total CPU time spent in the elements scheme
• The results presented were expected due to the less number of elements and consequently less integration points using shell finite element.

• The major interest of the present work is the 3D analysis of single point incremental forming process.

• The current work in progress is the application of adaptive remeshing using RESS finite element in an efficient and accurate simulation framework of SPIF processes for general 3D analysis.

• The near future work will be the use of unstructured meshes using the adaptive remeshing technique.
Thank you for your attention