Overcoming Major Obstacles of Springback Compensation by Nonlinear Optimization

Luca Hornung, Sebastian Denz, and Vojtech Cvrcek

Abstract The compensation of die surfaces to obtain parts that are dimensionally accurate after springback involves numerous serious challenges. In this article, we introduce a nonlinear optimization technique on mesh level that extrapolates a vector field defined in certain nodes to the whole mesh respecting defined constraints. This method is especially defined to preserve arc lengths as good as possible within the extension procedure. We apply this technique to all steps required in a compensation, the compensation of the blank against a target surface, the smooth modification of the tool surfaces, the treatment of undercut, and the application of fixing and symmetry constraints. Finally, we prove the flexibility of our vector field extension with an application to the offset problem of low-quality meshes. Last but not least, we discuss practical examples simulated in the commercial code Stampack Xpress.

Introduction and State of the Art in Springback Compensation

Springback occurs when the press opens and the elastic energy is released. This deformation results in deviations to the formed parts, that are often out of the allowed dimensional tolerance range. Usually, this is measured by comparing the final part after springback with the desired nominal part. Although there are many ways to reduce the springback effect like increasing blank holder forces, drawbead restraining forces, or introducing further plasticity in the part by reinforcement beads, springback cannot be fully eliminated. Thus, a common approach to get parts in dimensional tolerance is to modify the die surfaces by the amount of springback in opposite direction to the springback. The assumption of this approach is that the springback remains the same within this small modification and thus, the part is in tolerance.

L. Hornung (✉)
Stampack GmbH, Bietigheim, Germany
e-mail: luca.hornung@stampack.com

S. Denz · V. Cvrcek
Men at Work GmbH, Bietigheim, Germany

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In a ground-breaking work, Gan and Wagoner [2] introduced the so-called Displacement–Adjustment (DA) method that iterates several comparisons between target geometry and springback geometry in combination with the corresponding adjustments in the sheet and in the tool geometry. Several improvements to this method have been developed. Amongst others, we mention the smooth displacement adjustment method (SDA) by Petzoldt et al. [4]. This method improves the (DA) with an approximation method that provides continuous compensation displacement fields and a smooth extension from the blank area to the tool area. These two properties of the method are essential for a good compensation and will also play a huge role in our approach.

All these approaches are based on the following simple iterative idea that is visualized in Fig. 1. Imagine we have the springback geometry S_j after the j-th iteration, we measure the j-th displacement field D_j from target geometry to springback geometry. Then, we adjust the geometry C_j before springback by the vector field $-D_j$ to get the compensated geometry C_{j+1} of the next, the $(j+1)$-th, iteration.

A more recent and remarking approach for springback compensation is the physical displacement adjustment method by [1]. Their method is not based on modifying the blank node by node, but they deform the blank with forces normal to the blank in an additional elastic finite element simulation until they reach their desired compensated shape. The major advantage of this approach is that it preserves arc lengths and surface areas within the compensation process. They show that this enhanced method results in an improved compensation convergence compared to the existing commercial codes.

Major Challenges in Springback Compensation

Before we show the details of our approach, we first repeat the major challenges of springback compensation.

(1) Have a robust sheet metal forming process.
(2) Have an excellent springback prediction result.

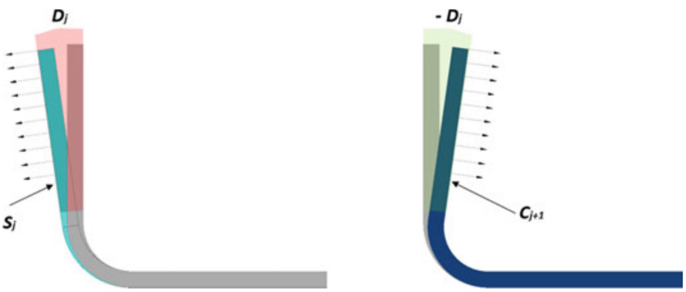


Fig. 1 **Left** distance to target after springback S_j. **Right** compensated geometry C_{j+1}

(3) Compensate the blank against a given target preserving arc lengths.
(4) Mapping the compensation from the blank to the tool surfaces.
(5) Applying constraints, for example, in the blank holder area.
(6) Remove undercut in compensated sidewalls.

Obviously having a solution for the challenges (1) and (2) is critical before coming to compensation. However, in this article, we focus on a new approach to solve challenges (3)–(6) with a vector field extension method based on a nonlinear optimization method that is described in the next section. Later on, we apply this quite general method step by step to overcome challenges (3)–(6).

Smooth Vector Field Extension by Nonlinear Optimization

We start with a triangular surface mesh S and a vector field V given in a subset of all nodes in the mesh. We assume that the magnitude of V is small compared to the size of the triangulated surface. Our method extends this vector field to a smooth vector field V^* defined on the whole surface S (Fig. 2).

The first step is to formulate the minimal conditions we have on our extension field V^*.

(1) $V = V^*$ on the set of nodes where V is defined.
(2) The extended vector field V^* should be defined in a way that the surface with node coordinates $S + V^*$ should be as close as possible to the surface with node coordinates S, i.e., the difference of mesh triangle sizes l and internal mesh triangle angles α between S and $S + V^*$ should be as small as possible.
(3) Additional linear equality constraints of the form $AV^* = B$ or linear inequality constraints of the form $AV^* \leq B$ for all choices of V^*, where A is a kxn matrix and B is a k-dimensional vector. Here, n is the number of nodes in S and k is the number of constraint nodes (Fig. 3).

Condition (1) describes the need to extend the vector field from a predefined base. Condition (2) leads to a nonlinear minimization problem. We use it to define a nonlinear functional ϑ of the form

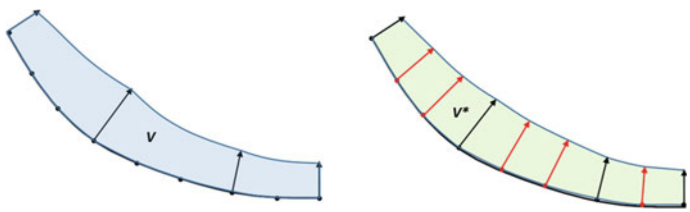


Fig. 2 **Left** vector field V in few nodes (black). **Right** extended vector field V^*(red)

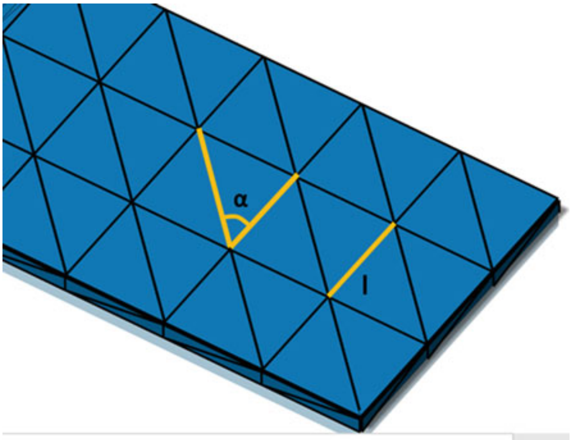


Fig. 3 Angles and lengths, to be changed as little as possible

$$\vartheta\left(V^*\right) = \sum_T \sum_{i=1}^{3} \vartheta_{1,T}\left(\left|\alpha_i(S) - \alpha_i\left(S + V^*\right)\right|\right) + \vartheta_{2,T}\left(\left|l_i(S) - l_i\left(S + V^*\right)\right|\right)$$

with a given error function $\vartheta_{1,T}$ and $\vartheta_{2,T}$ on each triangle T in S. These error functions depend on the displacement field V^* or more precisely on the triangle size changes and triangle angle changes in each triangle of the surface when we compare the surfaces with node coordinates S with the surface with node coordinates $S + V^*$. Condition (3) is not physically motivated. It is chosen as the maximum a state-of-the-art optimization solver allows. We will use this flexibility in our application to solve real-world problems. We solve this optimization problem with a constrained trust region solver with an initial guess given by a smoothed version of $V^* = V$, where V is defined and $V^* = 0$ in the other nodes.

The upside of this procedure is that due to Condition (2) it provides by construction a result displacement field V^* that provides a result surface $S + V^*$ that is smooth from triangle to triangle. Moreover, Condition (2) allows just minimal arc length deviations, a fact we need in our application to come closer to the great benefit of the physical compensation method, the length-of-line preservation, by Birkert et al. [1] than the traditional methods.

The application shows that our method is also stable in case of non-smooth input meshes S. However, due to convergence issues, this method is not applicable when the basic vector field V deforms the initial surface mesh too much. Hence, this approach is not applicable to general mesh morphing. Nevertheless, it turns out that it is sufficient for the springback compensation challenges and for offsetting die surface meshes by a sheet thickness. Before we show how to apply our extension method, we show an example where the arc length preservation is well illustrated.

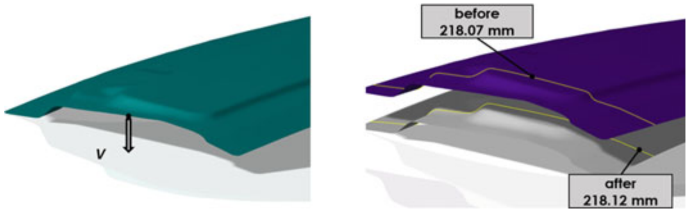


Fig. 4 **Left** vector field V on the surface S. **Right** comparison of the arc lengths between S and $S + V^*$.

Example: Windshield Cover

We take a 1 m large sheet metal part; a windshield cover; as surface S and we choose V in a simple way. V is defined in two nodes, one in the centre of the part and one in the centre of the arc highlighted in Fig. 4. We set $V = 0$ in the centre of the part and V is a deformation in $-$z direction by length 20 mm in the centre of the arc. Our extension procedure yields a deformation vector field V^* defined on the whole surface and we compare the arc lengths of the surface S and the surface $S + V^*$. The arc length changes in this deformation process from 218.07 mm on the initial surface to 218.12 mm on the result surface.

Application of Vector Field Extension to Springback Compensation

No matter how difficult springback is in practical applications, its magnitude is always small compared to the part size and the springback deformation is always smooth. Thus, it turns out that even for huge springback magnitudes occurring ,for example, in large automotive parts, the method provides excellent results. The key is to define the constraints in an appropriate way depending on what we want to achieve. Hence, we treat challenges (3)–(6) one by one with a different choice of the predefined vector field V, the area where V is defined and the constraints we impose.

Compensate the Blank Against a Target

It is well known [3] that springback can be compensated very well when the springback direction is normal to sheet, whereas it has limitations when the springback direction is more tangential to the sheet. Our approach is to choose V in the area where the springback is perpendicular to the sheet up to a tolerance (Area A). In this area, we set V as the inverted distance vector field from blank to target. The rest of the nodes are unconstrained (Area B). Our optimization scheme yields an extended

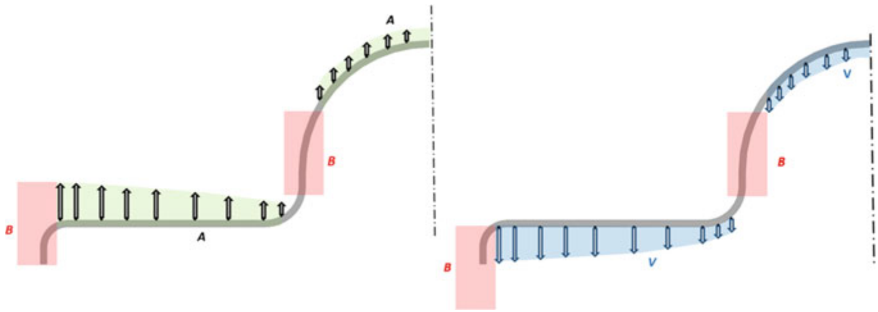


Fig. 5 **Left** springback perpendicular to blank in area A. **Right** compensation field V in area A

vector field V^* and we take $S + V^*$ as the compensated blank surface. In simple terms, we use the conventional displacement–adjustment method described in Fig. 1 in the areas where springback is almost perpendicular to the blank and treat the other areas with the optimization scheme (Fig. 5).

Extend the Compensation from the Blank to the Die Surfaces

In this step, the challenge is that typically the die surfaces are larger than the blank. Once we know how to compensate the blank, we map the compensation field from the blank to the area on the die that is in contact with the blank. Afterwards, we call our optimization algorithm with given displacement V in the area close to the blank and without constraint in the rest of the die. As a result, we get a smooth extension V^* of the compensation field to the whole die surface (Fig. 6).

Application of Constraints

Fixed areas, in real-world cases typically the blank holder area, can be obtained by defining $V = 0$ on the area to be fixed and to set an unconstrained smoothing zone around the fixed area as in Fig. 7. Outside the fixed area and the smoothing zone, V is defined as in Sect. "Compensate the Blank Against a Target". The optimization scheme then lets the fixed area fixed and provides a smooth extension to the rest of the part.

More sophisticated constraints, like a symmetry constraint in a certain area, can be achieved by using Condition (3) of our optimization scheme. Here, we enforce a symmetry in a predefined area and leave an unconstraint smoothing zone around the area with a symmetry condition.

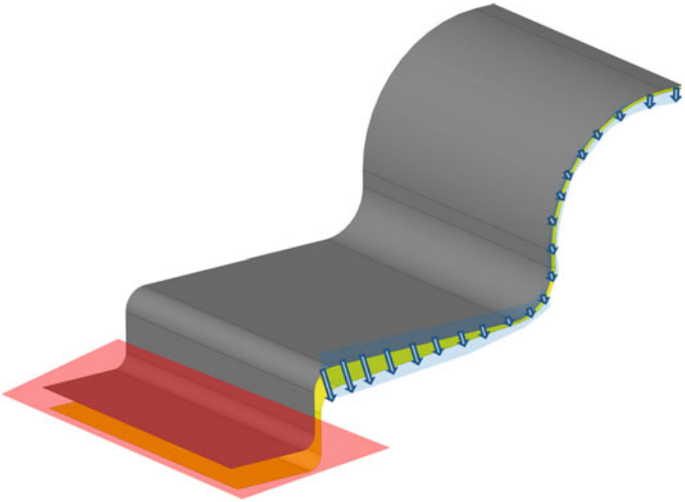


Fig. 6 **Grey** die before compensation, V is given by blue vector field, red zone is where V is not defined. **Yellow** die after compensation

Remove Undercut in Sidewalls

The linear inequality constraints are applied to remove the undercut, which is a constraint in our optimization scheme especially designed for sidewall areas. With this approach, we can treat areas that do not have undercut before the compensation

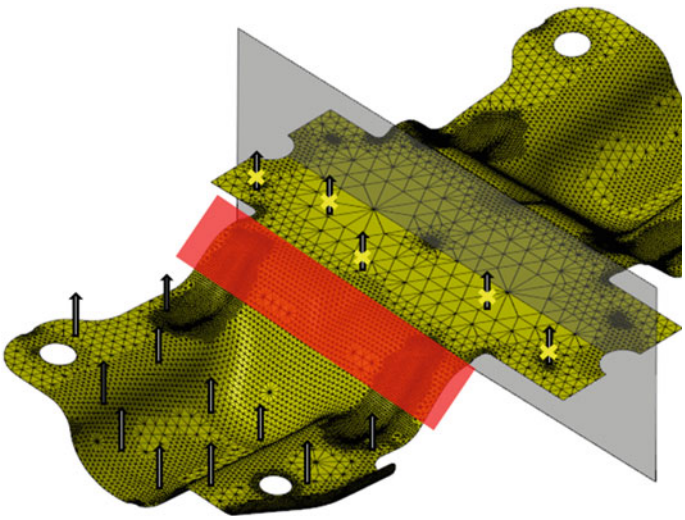


Fig. 7 Symmetric part fixed in the middle. Red zone is where V is not defined

and fall into undercut during the compensation procedure. To detect areas that fall into undercut, we take the following simple but useful criterion. We check in each node the normal vector n at node, and we say that a node has undercut if and only if the condition $n_z > 0$ before compensation and $n_z < 0$ after compensation holds true. This description can be used to define a constraint as in condition (3) together with an unconstraint smoothing area around the undercut zone. The optimization scheme forbids vector fields V^* leading to a surface $S + V^*$ with undercut. To get a smooth result, it is necessary to give an unconstraint smoothing area around the undercut area (Fig. 8).

Example: Springback Compensation of B-Pillar

We apply our method to compensate the springback of a B-Pillar. In this part, two iteration loops are sufficient to match the given tolerance $\pm 0.7mm$. We see that the distance to the target is not monotonously decreasing, but that the part that is initially above the target is then below. However, the absolute distance values are decreasing in a satisfactory way (Fig. 9).

Example: Flatness Tolerance in a Rear Wall Panel

The following example is a joint work with **Pengfei GmbH Deutschland,** a subsidiary of China-based **Pengfei Group** (www.pengfei-mold.com) with more than 2300 employees producing about 1000 tools per year for a worldwide customer base.

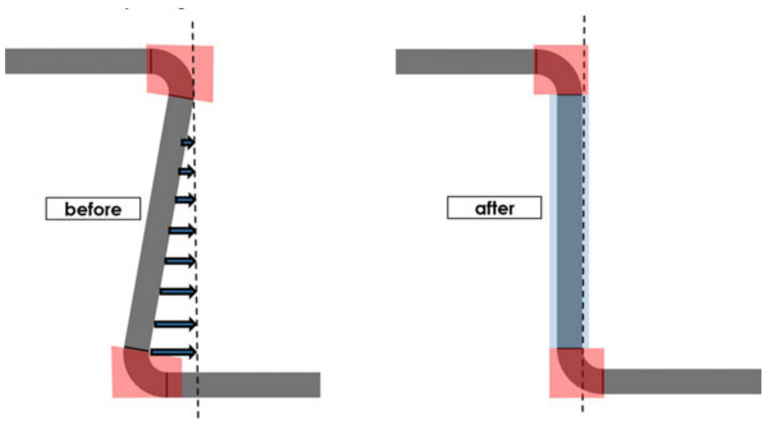


Fig. 8 **Left** vector field that avoids $n_z < 0$, Red zone is unrestricted smoothing zone. **Right** Result after undercut removal

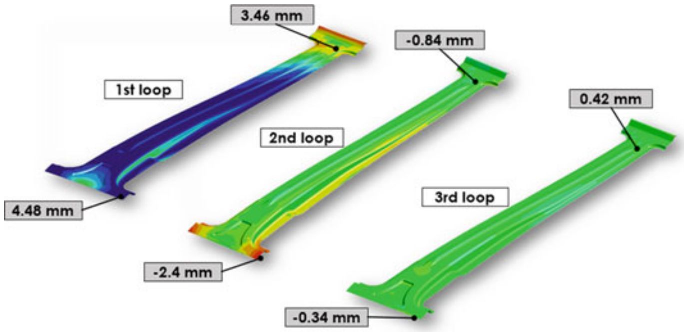


Fig. 9 Displayed is the distance to the target in each iteration loop

It is 345 mm large and 1.2 mm rear wall panel made of HX420LA. The challenge in this part is a flatness tolerance ±0.25 mm in the outer area, which is more than ten times smaller than the amount of springback. To compensate this springback from a simulation point of view demands a high accuracy of the forming simulation, an extremely precise prediction of springback and a good compensation algorithm. We choose Stampack's solid element technology with three elements across the thickness. The iterative application of our compensation algorithm converges in a base simulation and three correction loops to the desired accuracy (Fig. 10).

Example: Remove Undercut

The following example is an application of the undercut removal introduced in Chapter 3.4. It is a bracket made of the AHSS high-strength steel CP1400 with springback of 2.51 mm in the base simulation. The main difficulty is the vertical wall, that would fall into undercut in a naive compensation (Figs. 11 and 12). However, for production, it is mandatory to have tools without undercut and we have to apply our undercut removal. The convergence is again not monotone, the first correction is an overcompensation where just the absolute values are reduced. After the second correction loop, the part is in the required tolerance of $\pm 0.5mm$ and, after another loop, we end up with a part that is after springback just $0.18mm$ away from the target.

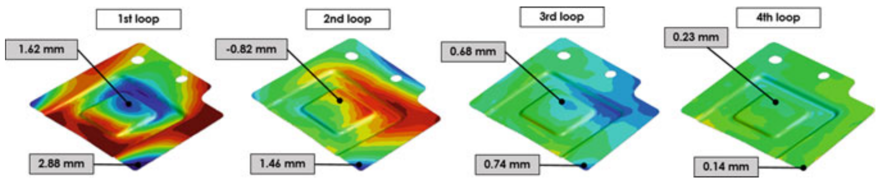


Fig. 10 Displayed is the distance to target each compensation loop

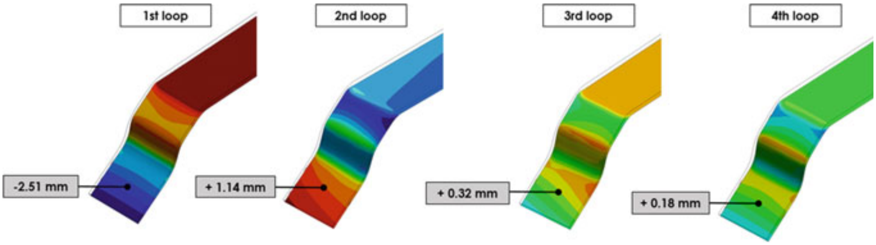
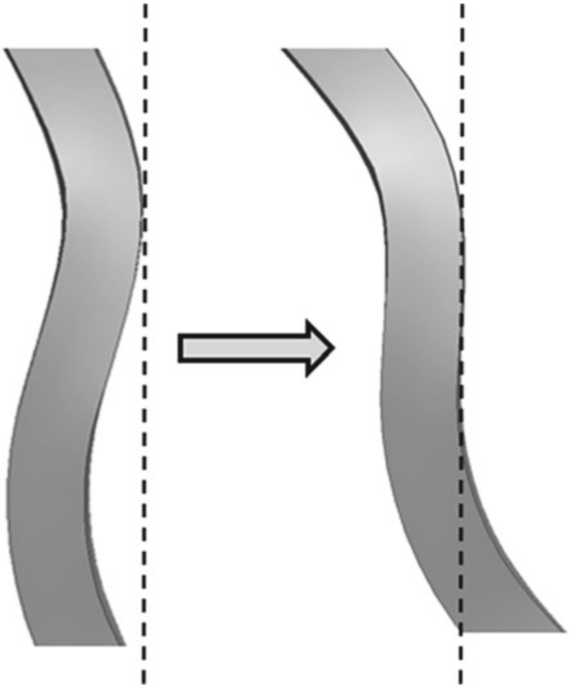


Fig. 11 Displayed is the distance to target each compensation loop

Fig. 12 **Left:** blank without undercut removal. **Right:** blank with undercut removal



Application of Vector Field Extension to Offsetting to Low-Quality Meshes

Another application of our extrapolation technique is the offset of low-quality triangular surface meshes by a small length. In applications, the offset length is typically the thickness of the sheet. Basically, offsetting a surface means to move each node in normal direction by the offset length L. Especially, when working with non-smooth tessellations, we face a huge problem. These meshes contain triangles with side lengths less than 0.002 mm, whereas we need an offset of 1–2 mm. A simple offset in normal direction would result in huge element distortions in these triangles (Figs. 13 and 14).

We approach this difficulty by covering the whole surface with patches. In each patch, we choose one node with a well-defined normal. Next, we set $V = normal * L$ in these nodes. Then, we extend V to a smooth vector field V^* in the whole surface and obtain the offset surface $S + V^*$.

It turns out that the limitation of our approach is the offset of sharp edges and more severely, the offset of a radius R by $L > R$ in contractive direction. In these cases,

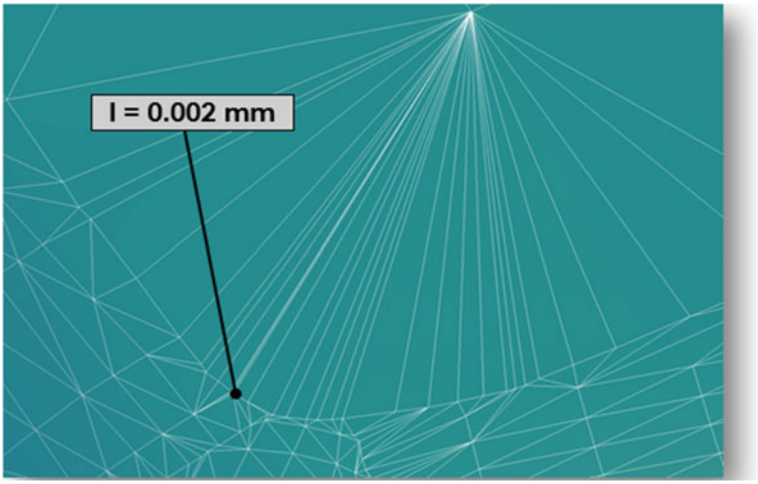
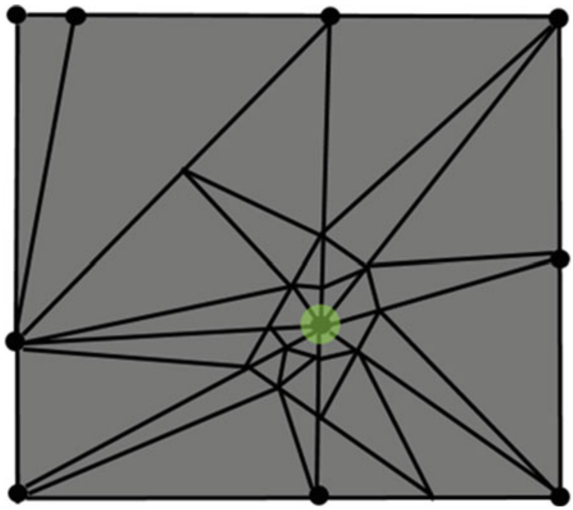


Fig. 13 Low-quality mesh

Fig. 14 V Defined in one node per patch



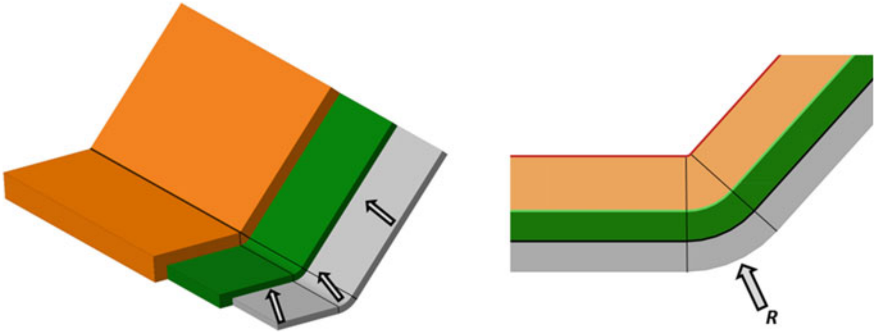


Fig. 15 **Green**: Offset by offset-length $R/2$. **Orange**: Offset by offset-length R with sharp edge

our approach fails due to triangle distortions in the offset surface. The borderline case $L = R$ gives in theory a sharp edge (see Fig. 15). In practical examples, we see that our approach is only stable when we have $L < 0.9 * R$. However, in typical sheet metal applications of automotive panels, this limitation is not that severe, since in these parts, we typically have radii much larger than the sheet thickness.

Conclusion and Future Work

We introduced a new approach to springback compensation. In the classical methods like the displacement–adjustment method, it was necessary to define for every node the appropriate compensation vector. In contrast, our method defines the compensation vectors just in those areas where springback is normal to the sheet and lets the optimization scheme finalize the job. We highlighted that this optimization method has the flexibility to extend the compensation from the blank to the larger die, to constrain defined areas and to remove undercuts in vertical walls. Finally, we apply the optimization scheme to the offset problem of non-smooth meshes. The limitation of our method is that a surface mesh cannot be deformed too much compared to the topology of the initial mesh. However, both springback compensation and offset of about 1–2 mm in automotive sheet metal parts do not require a general mesh morphing.

The method we propose is implemented in the commercial code Stampack Xpress. Still open is a detailed comparison between our approach and the other commercial and non-commercial methods to distinguish the strength and weaknesses of each method. However, we are confident that our springback compensation by nonlinear optimization opens a new way of thinking about springback compensation.

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