The application of a newly modified numerical global springback compensation method

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Abstract. A newly modified numerical global springback compensation method was used to simulate the die process in this paper. The numerical approach is given to evaluate the compensation matrix, and the matrix changes according to forming deviations. And GC remedies quasi Newton (QN) method’s sensitivity to initial die contour. To verify its effectiveness, GC, DA and QN have been used to design dies for a series sheet metal parts with cylinder, sphere and saddle shapes. Summarizing simulation and experiment results, the method in general converges faster and more stable.

1. Introduction
There are several means to reduce the dimensional error caused by springback. Some of them tried to eliminate springback by modifying forming processes[1-2]. Some of them attempted to increase the blank holder pressure or use inverse approach in deep drawing process to limit the error[3-4]. However, their application may be restricted by parts’ materials and shapes, although these methods possess the benefits of convenience in die design.

GAN and WAGONER [5-6] proposed displacement adjustment(DA) method, whose concept is to move the die surface nodes in the direction opposite to the springback error. The distances and directions that die nodes move along were not specified in the concept. And according to different compensation magnitudes and directions, a series version of DA algorithm can be derived. In the first version, compensation is only made in the y direction, which is parallel to the punch travel direction[7]. And the shape error is added directly to the current die shape nodal positions. This method converges faster than “spring forward” algorithm and exhibits stabilization for cases involves large springback shape changes and non-symmetric parts[8-10]. It deviates a lot from the right direction in V-bending [10]. The third type of compensation direction relates to normal orientation. This method is still feasible when there is no mesh nodes available, such as cases that tools’ shape are described by point clouds in reverse engineering or CAD geometries[9]. Contrary to the RD approach, it works well in V-bending cases, where rotation is the main phenomenon during springback, but would have a poor performance when displacement direction deviates from the normal orientation[7]. Besides this, calculation normal direction needs extra work, so it is not a readily measure as the former two.
Another way of utilizing normal directions to compensate springback is the comprehensive compensation (CC) presented in Ref.[11]. Being different from moving nodes in normal directions, this method takes the difference of normal orientations of die contours and that of part shapes into consideration. As figures in the paper illustrated, its performance was better than several current methods. However, far more work is needed to put it into practice. Because not only calculating distinction of normal directions but also an angle factor for an optimal compensation direction are necessary in the approach.

The compensation factor was extended to a compensation matrix in the DA method in this paper. By doing so, not only both compensation magnitude and direction, but the global issue of spring back is taken into account.

2. Numerical Simulations

In order to test the effectiveness of the proposed compensation method, a series of cylinder, sphere and saddle parts were subjected to die design using GC, QN and DA. Three methods all compensate along three coordinate directions. The compensation factor for DA method is 1.0. For GC, \( t_i = 0.05(i-1), i = 1,2,\cdots,21, A = 0.01 \) and \( \lambda = 0.1 \).

2.1. Cylinder cases

In the simulation, FEM simulations were performed with ABAQUS. Compensation methods, DA, QN and GC, were implemented through a MATLAB program. The sheets were loaded by a 20MPa pressure to ensure fully contact with the single die. A single sheet was meshed with 300 S4R shell elements and 5 integration points in its thickness direction. The material used was aluminum alloy 2124T851, whose properties came from Ref.[19]. The Young’s modulus is 69251MPa, Poisson’s ratio is 0.33. The dimension of sheets was 150×50×2mm. Compensation iteration stopped when the absolute shape deviation was lower than 0.8mm.

As shown in Fig. 1, GC needs less FEM calculations than DA method in all five radius and converges faster than QN method in most cases. Fig. 2 illustrates the result of GC in R=800mm cylinder case. As shown in Fig. 2, the die shape changes small in the first compensation, large in the second one and small again in the third one. The changes satisfy the expectation that die shape changes large when it is away from the desired one, and it changes small when close to the desired one.
Cylindrical parts with radius 800mm, 850mm, 900mm and 1000mm were subjected to die design with a tolerance ±0.8mm through the three methods. Multiple radius were chosen to test methods’ sensitivity for initial die contours. And desired part shapes were employed as initial die contours. Fig. 1 shows the maximum absolute shape error for each FEM calculation. There are two loops in Homotopy method. Here, times of FEM calculation rather than iteration are taken into account, since it is much more time-consuming than other computation.

2.2. Sphere cases
In the spherical simulation cases, the settings were nearly the same to the cylindrical cases, except parts using here were spheres with radius 800mm, 850mm, 900mm and 1000mm. And if iteration consumed more than 7 FEM calculations, computation would be stopped. The results are shown in Fig. 3 and Fig. 4. Again the GC demonstrates good performance. Generally speaking it converges fast among the three approaches. The DA method needs one or two more FEM calculation than that of the GC. The main difference is in the QN method. Except the case with radius 900mm, the QN method consumes more than 7 FEM computations and does not show traces of converges. This is attributed to its nature of local convergence.Fig. 4 shows shape changes of die and part during the GC iteration with radius 900mm sphere. Since part shapes are three dimensional in this section, only center contours along direction of parts’ length are shown in Fig. 4. In the first three FEM calculations, the die contour changes small. However, it converts dramatically in the last FEM calculation. Referring Fig. 3, shape error begins to change large in the third calculation. This indicates that small changes in die shape can leads to big changes in part’s shape error. There is non-linearity between shape error and die shape. Therefore, the DA method is an attempt to copy a nonlinear problem with a linear approach.

2.3. Saddle cases
The last set of cases employed in numerical simulations was parts with saddle shape. Here, saddle represented another type of double curve parts who have curvatures in two opposite directions. Identical radius was selected for the two reverse orientations. Therefore, utilized parts could be referred by saddle parts with radius 800mm, 850mm, 900mm and 1000mm. The results are shown in
Fig. 5 and Fig. 6. Through several iterations have cost 7 FEM calculations; they all reached the desired shape error. Contrary to its poor performance in sphere cases, the QN method resumes converges faster than the DA method in saddle cases. And the GC is the fast approach in three fifth of all saddle cases. Since the GC method uses a modified quasi Newton method to solve homotopy equation, it over-predicts compensation magnitudes in some cases as what the QN method does. These cases are shown by saddle part with radius 800mm and 1000mm in Fig. 5.

Fig. 6 shows shape changes of die and part during the GC iteration with radius 850mm saddle. It reflects an ideal situation for the idea that attempts to accelerate compensation by modifying compensation factor (matrix) according to shape error. That is to evaluate the compensation matrix with the initial two FEM calculation results and the third FEM calculation meets the required shape tolerance.

Figure 5. Comparisons of shape error between three methods for five saddles. Figure 6. Results from GC, saddle R=850mm.

3. Application of the method
To verify the accuracy of the modified numerical global spring back compensation method, the forming process was carried on a hydraulic forging press. The die was made of low carbon steel and several layers of rubber covered on the sheet metal to simulate pressure loading condition, as shown in Fig. 7. Based on the modified method, the spring backed sheets were processed sequentially in the order shown in section 2, and the result was shown in Fig. 8. Comparing experimental results from sheets with approximate size in Ref.[20] and Ref.[13], the result is content.

There are several causes for the deviations in Fig. 8. First, due to limits of equipment, the Young’s modulus is not precisely measured. Second, parameters of 304 stainless steel used in experiments is not perfect consistent with each other. Third, the FEM model employed in the springback compensation program also has errors. Through to improve FEM model’s accuracy is beyond this paper, it does have influence on the experimental results.
4. Results and discussion

Contrast to other classes of compensation methods, which tend to predict the tooling shape based on local stress/strain information of the last forming increment\[20\], the DA, QN and GC methods employ last forming shape deviations to do that. Compared with DA method, in GC and QN method, compensation coefficient has been extended to a compensation matrix that is called Hessian matrix. Through doing so, compensation magnitudes are not unified in the die’s mesh nodes and are adjusted according to the deviations in every iteration. Furthermore, the compensation magnitude in a node is not restricted to a multiple of deviation in the very node, but a linear combination of deviations in all die nodes. The latter is more reasonable than the former. Since springback is a global issue of the entire sheet\[20\]. The forming result on a certain die node is at least related to nodes around it. Hence, with above factors combined together and in certain type of cases, GC and QN method converges faster than DA method.

Besides the algorithm to solve forming equations, another difference comparing the approach used in Ref. \[4\] is the compensation direction. In Ref. \[4\], the nodes in die’s contour mesh was only adjusted vertically. So a group of y coordinates represented the die shape. It was suitable when parts’ curvature is small as age forming cases studied in Ref.\[4\]. To expand its application, all three coordinate directions, x, y and z, are utilized to describe die shape and they are arranged to an array as showed in Eq.(5). Since elements in compensation matrix varies, the actual compensation direction of a certain node is a linear combination of x, y and z. It changes with elements in compensation matrix. So compensation direction adjustment can also be achieved by utilizing the concept of compensation matrix.

To compare performance of the three methods when compensation is only made in stamping direction (y direction), three parts with radius 900mm cylinder, sphere and saddle parts were subjected to die design. Other setting was the same as in section 3. The results are shown in Fig. 9. The only method whose results changed significantly is the QN method. In cylindrical and spherical cases, QN yield divergence results, which converged using three coordinates. While GC and DA method remains stable.

Besides the instability, there is a key defect in QN method when it is applied in springback compensation. Quasi Newton method is a local convergence algorithm in numerical analysis, that is to say, the initial contour used in the iterative program should be close enough to that of the die producing parts satisfying design. Otherwise, the die contour sequence generated by the program will not converge, as shown in Fig. 2. It is a harsh request, because a close-enough die contour is difficult to design when designers do not know the contour that it needs to be close to. For the same reason, these iterative springback compensation methods usually employ parts’ design shapes in initial tryouts. The GC, however, is a global convergence algorithm. With same initial die contours, it can converge to the desired die shapes when QN cannot.

Although Quasi Newton algorithm is employed in the GC to solve homotopy equations, there is an improvement compared to the algorithm in Ref. \[4\]. A damping parameterλI is introduced into the
method. It can suppress, though not eliminate, that shape error drastically increases, as those in the third FEM calculation of QN method. The damping parameter improves GC’s performance. However, it is not the only cause of its advantages over the QN method. To illustrate this, diverged cases in section 3 were recalculated with QN, which had damping parameter. All four cases, spherical parts with radius 800mm, 850mm, 950mm and 1000mm, still did not converge as shown in Fig. 10.

5. Conclusion
In this paper, a new global method based on compensation matrix was proposed. In the method, homotopy algorithm was used to calculate die shapes iteratively and a damping parameter was introduced into the method. The method converges faster and is not sensitive to the initial die contour. The new method was compared with the displacement adjustment method and the quasi Newton method. The following conclusion could be made from the results:

(1) Compared with displacement adjustment method, in which compensation magnitude and compensation direction were important aspects, the compensation factor had been replaced by a compensation matrix. It enabled different compensation magnitudes and directions for different nodes.

(2) The compensation was not only based on the information of the very node but also from other nodes in the entire part. This fit the global nature of the springback problem.

(3) The new method also used a numerical approach to evaluate the compensation matrix based on forming shape deviations. Theoretical computation of the matrix would be included in the future work. And the method would be used in practical parts, such as creep age formed aircraft integral panels and automobile panels.

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