Structural springback analysis of car body closure assemblies using finite element process chain simulations

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Abstract. In recent decades, numerical simulation methods have become increasingly important in car body engineering to achieve the high dimensional quality requirements for closure assemblies like bonnets, doors and tailgates. In order to model the entire manufacturing process, latest research works have been focusing on combining the finite element-based simulation models. These complete process chain simulations are able to predict the springback behaviour of the assembly before the physical realization of the tools and processes. The purpose of this study is to introduce a method to use finite element process chain simulations to analyse the structural springback behaviour of car body closure assemblies. Therefore, the numerical process chain simulations are combined with statistical and stochastic tools in order to develop a meta-model, which represents the dimensional accuracy of the investigated assembly. The presented method will then be schematically advanced to be ultimately used in different application areas like robustness and tolerance analyses.

1. Introduction and incentive of work

The numerical, finite element-based simulation methods have become the most powerful supporting tools to validate the feasibility of single sheet metal components, predict their springback behaviour after forming and analyse the robustness of the manufacturing process. These simulation results provide valuable insights for the tool design and are basis for different compensation strategies to improve the part quality. However, practice shows that the joining of single components, each in its dimensional tolerance, does not necessarily lead to a dimensionally stable assembly. Determined deviations in the joining processes are continually reassessed and have to be compensated if outside specified tolerances. These subsequently performed optimization measures lead to many time-consuming and costly manual quality loops in the corresponding process steps in the press and body shop. The determination of a suitable compensation strategy also requires specific expertise and knowledge of the personnel. Therefore, latest research has been focusing on advancing the established numerical single component validation to predict the springback behaviour of sheet metal assemblies by linking the individual simulation steps to a process chain simulation [1, 2, 3, 4, 5].

Such a comprehensive modelling of all manufacturing processes already allows an estimation of the resulting dimensional quality of the assembly for a predefined data set of input variables and the derivation of an iterative and backward-oriented compensation strategy. This means that occurring dimensional deviations are evaluated stepwise and a strategy for their compensation is retrospectively defined and realised. There are no reference criteria for the effectiveness of the executed compensation
measures at that time. Furthermore, no process fluctuations like alternating material parameters have been considered.

The purpose of this study is the introduction of a method to analyse the structural springback behaviour of car body closures made of sheet metal components by using finite element process chain simulations. The numerical models are therefore supplemented with statistical and stochastic instruments in order to develop a meta-model, which represents an analogous dimensional model of the investigated assembly. The presented method is illustrated schematically in figure 1.

Figure 1. Schematic diagram for the structural springback analysis of car body assemblies.

The concept of the developed method will be presented on the example of a structural springback analysis of a car bonnet assembly by modification of the active surfaces of the deep drawing operation of the inner part as shown in figure 3. Nevertheless, the presented method is applicable for each of the modifiable input parameters of the process chain simulation.

2. Finite element process chain simulation of a car bonnet assembly
The process chain simulation developed for this investigation is based on the serial production process of the former car bonnet assembly of the Opel Adam (model year 2013-2019, figure 2). It includes the forming simulations of all single components, the joining simulation of the reinforcement parts with the inner panel to the subassembly as well as the roller hemming simulation of the subassembly with the outer panel. The process chain simulation is modelled using different test version software programs provided by AutoForm in order to consider multiple elastic sheet metal components. Remeshing and data mapping can be avoided that way because of using compatible finite element software codes in all programs. As a result, also specific tensorial simulation values linked with mesh nodes like residual stresses can be considered consistently throughout the whole process chain simulation which significantly improves the reliability of the springback simulation results. The prediction accuracy of the process chain simulation has been validated in preliminary studies [5] and will not be part of this work. A high consistency of the process chain simulation results with the real manufacturing process is essentially important for the development of a representative meta-model to predict the structural springback behaviour of the investigated assembly.
3. Design of experiments

The aim of the design of experiments is to define a suitable scope of investigations in order to develop a meaningful and precise meta-model. Figure 1 shows a selected collection of possible modifiable input parameters that have an influence on the structural springback behaviour of an assembly. The more input parameters are selected to be variant, the more combinations of the different resulting input parameter combinations are possible. This can soon lead to an extremely high variety of factor level combinations. Considering the currently available limited computing capacity, not all of these combinations can be calculated with a process chain simulation. Therefore, the number of performed simulation runs that need to be executed have to be significantly reduced to a required minimum. An appropriate practice is the use of sampling methods like the Latin-Hypercube-Method (LHC).

![Figure 2. Developed process sequence and components of the investigated car bonnet assembly using different test versions of AutoForm [6].](image)

![Figure 3. Design of experiments to investigate the structural springback behaviour of the assembly by modifying the active deep drawing tool surfaces of the inner part in defined areas with corresponding standard distributions.](image)
The LHC assumes a theoretical distribution of the input parameters (e.g. standard distributions figure 3) and divides them into N intervals of the same probability of occurrence. Then, a cumulative probability of each interval is taken as a sample. Range of the permitted values and distributions are usually based on statistical evaluations (e.g. material properties) or empirical values based on the experience of the operator (e.g. clamping point positions). The number of samples taken in each interval equals the number of variants. Consequently, the LHC systematically selects the input parameters within defined tolerance limits. The application of the restricted pairing algorithm [7] also allows to consider known dependencies of input variables (if applicable) or to perform a sensitivity analysis to find correlations between them. Subsequently, the samples are combined through a so-called permutation like the pairing method to a test plan with a total of N simulation runs.

As shown in figure 3, a total of eight areas are selected to be modified within randomly specified limits \(x_{\text{min}}\) and \(x_{\text{max}}\) and standard deviations \(\sigma\). The scope of experiments is set to a total number of N=20 simulation runs. The application of the LHC with chosen input parameters leads to the design of experiments as illustrated in the table. The generated values refer to the equivalent modification value of the active deep drawing tool surface in the different areas for each simulation run (in mm) according to principle shown in figure 4.

![Figure 4](image4.png)

**Figure 4.** Manipulation principle with predefined boundary conditions (left) and resulting tool mesh after morphing with OptiStruct™ in HyperMesh™ (right) [8].

For a total of 20 simulation runs as specified in figure 3 an equivalent number of active tool surfaces with corresponding modification values have to be derived from the nominal deep drawing tool. The generation of the 20 different active tool surfaces with specified modification values in the different areas is realised by a manipulation of the meshed tool surfaces with the OptiStruct™ solver from Altair in HyperMesh™. Figure 5 shows the resulting springback of the car bonnet assembly in run 18 after modifying the inner parts active surface by the highlighted values in figure 3 according to the manipulation principle in figure 4 (outer panel and reinforcement parts are omitted).

![Figure 5](image5.png)

**Figure 5.** Resulting springback result of process chain simulation run 18 with modified deep drawing tool mesh of the inner part.
The evaluation of the maximum and minimum springback values in selected measuring points of all 20 process chain simulation runs already allows a first approximation of the structural springback behaviour of the investigated assembly. These measuring points are randomly selected on the assembly’s edge to get a general overview of the matching to other car body structures and components.

**Figure 6.** Evaluation of the structural springback behaviour of the assembly by modifying the tools active surfaces of the inner part (deviation to nominal in z-direction in mm).

Figure 6 shows the influence of modifying the inner parts deep drawing tool areas on the springback results of the 20 process chain simulations in the evaluated measuring points. The blue dots indicate the average distortion of the measuring points throughout all simulation runs. In consideration of a dimensional assembly tolerance of +1mm (red lines in figure 6) it is clearly shown that these input parameters would lead to a non-acceptable part quality.

4. **Interpolation of the meta-model via Kriging**
Kriging is a spatial interpolation method originally proposed by Daniel G. Kriege for a statistical approach to data mining. It assumes that similarities do exist between spatially adjacent values [9]. It presumes that measuring points close to each other have a higher influence on each other than those further away. In this context, Kriging implies a continuous transition between two measuring points. This interpolation technique figuratively describes a structural material behaviour. Therefore, it is
almost predestined to be used to fit the assemblies springback results of the executed process chain simulations into a meta-model. This derived analogous model is ultimately able to deliver a stochastic approximation for the expected springback values of the assembly for any inserted input variables considered in the design of experiments (although not tested before). The fundamental principles of the Kriging method can be looked up in [10].

The consideration of 8 defined modification areas over 20 simulation runs (figure 3) and the evaluation of 42 measuring points (figure 6) lead to a data set input matrix of 8x20 and a data set output matrix of 42x20. Therefore, it makes sense to transfer the resulting Kriging model into a statistical data program like Microsoft Excel. This also allows to link the output variables to cells with input variables with the Kriging Model as implemented formula. The influence of changing input parameters on the output variables (springback values) can then easily be evaluated with a solver by automatically alternating the values within the defined range.

![Figure 7. Automated solver-based variation of input variables to investigate the structural springback behaviour of the assembly.](image)

This solver-based variation of input variables can now be linked with any logical function in form of a target function to find out the range of the input variables that meet the specified requirements. For example, the maximum and minimum allowed modification values of each area to meet the dimensional part tolerances of the assembly.

5. **Outlook**

The purpose of this study was to introduce a method to analyse the structural springback behaviour of car body closures made of sheet metal components by using finite element process chain simulations. This method has been schematically demonstrated on the example of the modification of the inner parts deep drawing tools active surfaces of a car bonnet assembly. The definition of the target function (figure 7) thereby defines the goal of the investigation. It could possibly be defined as a maximum allowed dimensional deviation of the measuring points within a specified part tolerance (tolerance analysis) or a minimization of the deviation in all points (compensation strategy). As shown in figure 1, the concept can be applied to any imaginable input variable that has an effect on the springback of the investigated assembly. Presented method is also not limited to predict springback values, it can also be extended to evaluate any simulation result of interest that can be numerically evaluated.
The bottleneck of the methods application is the generation and calculation of a sufficient number of variants in order to interpolate a suitable and meaningful meta-model to represent the springback behaviour of the assembly. The creation of the variants for the different simulation runs and their evaluation have to be manually carried out so far and are limited to the current calculation and storage capacities. Therefore, an implementation of proposed method in a single software solution is recommended in order to parallelise the calculation of different simulations runs and automatically evaluate defined simulation results.

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