

CASE STUDY // ELECTRICAL ENGINEERING

OPTIMIZATION OF A CONNECTOR

With ANSYS optiSLang, an automatic material calibration and optimization for a connector was conducted including a subsequent tolerance analysis.

Task Description

Connectors are used in a variety of industrial fields like eMobility, power automation or automotive industry. By optimizing the geometry of connector designs, a required insertion and pull-out behavior can be achieved. In addition, the quality of the connector must be verified. With the help of ANSYS optiSLang, engineers can efficiently meet these challenges. This article describes how to set up and perform an automatic material calibration and optimization for a connector including a subsequent tolerance analysis.

First, a connector optimization usually involves a material calibration, for example, as part of a tensile test. The aim of the material calibration is to find a parameter set for the description of the material law resulting in a reference tensile test curve that can be fitted as optimally as possible. The material calibration for a tensile test of spring steel has already been performed and is described in the step-by-step tutorial "spring_steel" which is included in the installation of optiSLang. Here only a brief result presentation of the material calibration. Five material parameters describing the complete elastic and plastic material behavior were calibrated. Figure 1 shows the force-displacement curve from the tensile test (green) to which the fitting was

conducted and the curves from the simulation (grey). The result of the material calibration is shown in Figure 2. The almost congruent curve of the optimum (red) compared to the reference curve (green) shows the excellent fitting. The calibrated material will be used for the following simulations. Here, the connector optimization intended to achieve a desired insertion and pull-out behavior.

For the optimization, a fully parameterized 2D CAD model with 15 geometry parameters was generated in Design Modeler. Figure 3 shows the design of the connector, exclusively under consideration of the current-carrying parts without plastic components. Based on the CAD model, a FE model was then developed in ANSYS Workbench using automatic meshing. Component 1 was defined to be fixed on the left side. The load case included two load steps with axial displacement. Component 2 performs an axial movement in negative x-direction for connection and in the reverse direction for separation. The insertion and pull-out processes result in a force-time or force-iteration curve as shown in Figure 4.

After half of the iterations, the performance changes from inserting to pulling out, i.e. the inserting process starts with iteration 0 to 50 and the pull-out process goes

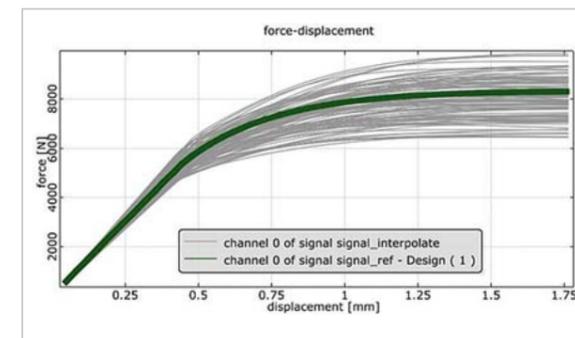


Fig. 1: Force-displacement curve from sensitivity analysis (grey) in comparison to the reference curve (green) of the tensile test

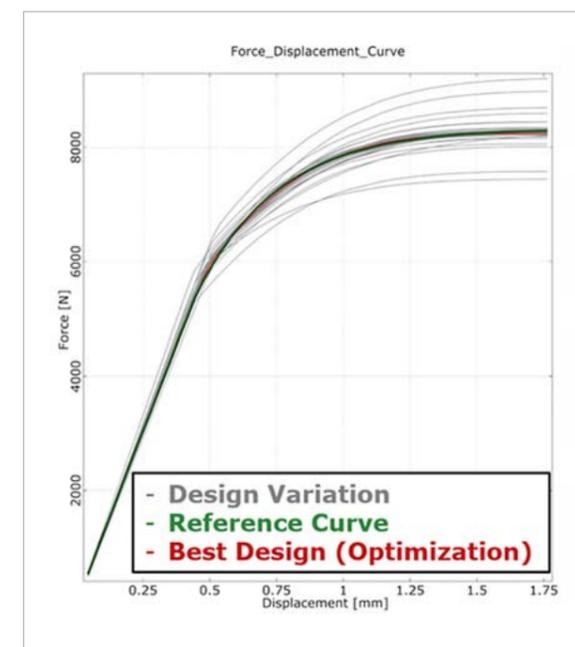


Fig. 2: Force-displacement curve of the optimum (red) compared to the reference curve of a tensile test (green) and the other curves obtained from the optimization (grey)

from iteration 50 to 100. The connecting process is described by a negative force curve at the beginning followed by the snapping process with a positive force curve. The pull-out process is described by the positive force curve at the beginning of the second half of the curve followed by the snapping process with a negative force curve.

The aim of the iteration is the minimization of the deviation between the reference curve and the simulation curve. The reference curve (green curve in Fig. 4) corresponds to a selected desired behavior and was not derived from a test as it would be done in a material calibration.

Name	Type	Expression	Criterion
objective	Objective	$\text{euklidnorm}(\text{vector_insertion_ref}-\text{vector_insertion})+\text{euklidnorm}(\text{vector_pull_out_ref}-\text{vector_pull_out})$	MIN

Fig. 5: Definition of the optimization objective in ANSYS optiSLang

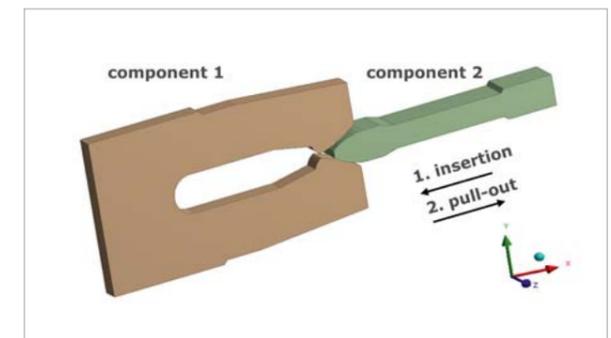


Fig. 3: Simplified parametric model of a connector with the current-carrying components without plastic components

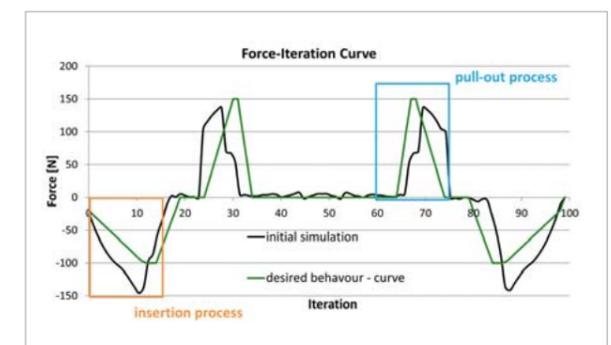


Fig. 4: Force-iteration-course of the reference curve (green) and of the initial design (black) of a connector with marked areas for insertion and pull-out process

The minimization should also only be carried out in the marked areas (orange and blue rectangle in Fig. 4), which means the snapping actions are not taken into account. The initial design (black curve in Fig. 4) has a too high insertion force compared to the retention force. The gradient of the inserting process is very steep, whereas the gradient should be steeper during the pull-out process. The following points were aimed regarding the reference curve in comparison to the initial design:

- Constant and lower gradient during insertion
- Lower insertion force (2/3 of the holding force)
- Constant and higher gradient during the pull-out process
- Higher holding force of 150N

Design of Experiments and Sensitivity Analysis

A sensitivity analysis is conducted to determine the significant correlations between the result variables and the input parameters. In this case, 15 geometry parameters in the Design of Experiment (100 designs, ALHS) are varied in a pre-

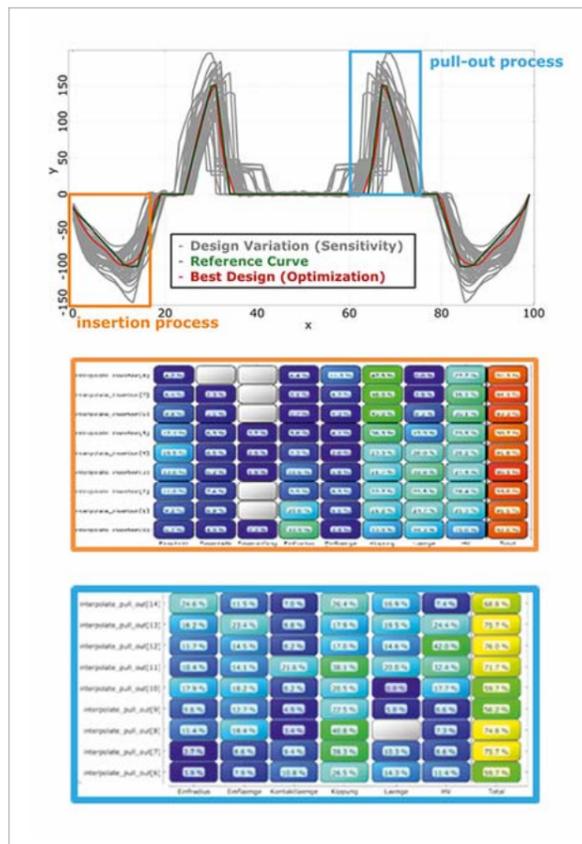


Fig. 6: Variation of the force time curves from the sensitivity analysis (grey) compared to the reference curve (green) and to the optimal design (red) from the direct optimization with the CoP matrix for the important marked area of the insertion and pull-out process as a result of the sensitivity analysis.

defined range using the software product ANSYS optiSlang 7.1.0. The resulting force-iteration-curve and the image of the created geometry are saved for each geometry variation. No "failed designs" appeared among these 100 designs.

The sensitivity analysis generated signals and vectors as result values, i.e. no scalar quantities. For the signals, these values are the defined reference signal and the respectively determined simulation signal. Both signals are used for visualization and for extraction of vectors. The sum of the squared deviations between the desired and the calculated data for the required time steps (marked areas in Figure 4) is additionally considered as a result variable, separately for inserting and pulling-out. The definition can be seen in Figure 5 (see previous page) and is also used later in the optimization as an objective. As explained above, the deviation is located not between signals but between vectors. The vectors correspond to the extracted ordinate values of the constant reference signal and of the variable simulation signals.

The advantage of the vectors' use is the minimization of deviation and the setup of an individual MOP for each vector component. Thus, it is further detectable when and in which direction which input parameter exerts influence. The deviation of the vector components is calculated separately for insertion and pull-out process and then added together.

The discretization and length of the vectors is identical. A weighting of the two summands and thus a weighting between insertion and pull-out is not conducted. Additional boundary conditions (constraints) are not defined. Since the optimization objective has already been set up in the sensitivity analysis, the results can be analyzed immediately.

An important aim of the sensitivity analysis with regard to calibration was to ensure that the variations of the simulation model completely covered the reference curve in the important abscissa area. This secures an optimal fitting during the optimization process within the limits of the chosen parameter set. Figure 6 shows this accomplishment in the two considered areas. The reference curve (green curve in Fig. 6) is covered by the simulation curves (grey curves in Fig. 6) within the marked areas.

The considered abscissa area of the inserting and separating process is segmented into 18 equivalent steps and results in 18 vector components. A larger vector component correlates with a larger abscissa value of the signal. This can be used to determine, which input parameter has an influence on the signal characteristics. Every second vector component inside the two CoP matrices is shown in Figure 6. The change of influences within the signal course is recognizable. Regarding their significance, the CoP matrix for both load cases shows only 8 input variables for the inserting pro-

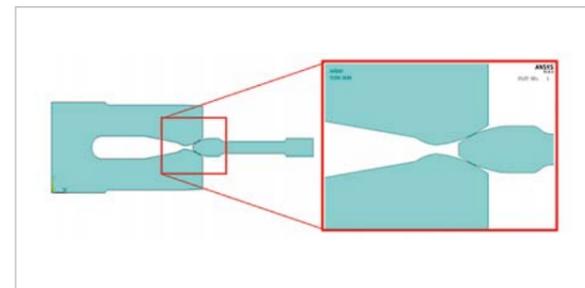


Fig. 7: Representation of the connector geometry for the optimum design from the direct optimization, with a detail of the contact zone

cess and 6 input variables for the pull-out process. Thus, started with 15 emanated geometry parameters, a strong reduction to the most important and less important input parameters could be achieved. All input parameters, which are not displayed here, are unimportant for the presented responses and are automatically filtered out.

Without going into more detailed examination of individual sensitivities, generally high total CoP values above 92% can be stated for the insertion process. This indicates a high degree of explicability of the essential physical phenomena by the identified correlations. With total CoPs between 56 - 76%, the pull-out process does not show such a high degree of prognosis quality. This is a result of the large geometry variation, which creates unfavorable designs causing a gradual increase of the pull-out force.

Statistical Data	Min Value [N]	Max Value [N]	Target Value [N]	CoV [%]
Insertion	79	118	100	7
Pull-Out	125	180	150	7
Statistical Data	Sigma Level for Safety Limit 110N	Sigma Level for Failure Limit 130N	Sigma Level for Safety Limit 135N	Sigma Level for Failure Limit 105N
Insertion	1,57	4,34		
Pull-Out			1,73	4,46

Table 1: List of statistical values for the maximum insertion and pull-out force determined from the tolerance analysis

Single-Objective Optimization

With the knowledge of the significance and sensitivity of the calibrated input parameters, further optimization can be performed to improve the system or product design. Because the optimization objective has already been defined and analyzed in the sensitivity analysis, start values and start designs can be immediately selected for the optimization. Further, the sensitivity analysis leads to a reduction of the designs, i.e. a reduction of input parameters and input variation. All three reasons lead to a decrease of computing time for the upcoming optimization and the optimal design can be found much faster. Due to the low degree of explicability of the pull-out process, an optimization on the MOP could not be continued. For the optimization, a direct optimization with the Adaptive Response Surface Method (ARSM) is chosen.

Input parameters that do not show any influence on the response variables during the sensitivity analysis are not included in the optimization. However, they are taken into account with their reference values. In Figure 6, the optimization carried out with the best design curve (red) shows a high accordance with the desired curve. Regarding the insertion process, a decent fit exists at the maximum insertion force. Unfortunately, the desired insertion force does not fit very well. This is due to the rounded surfaces of the modeled contact area, where a linear increase of the insertion force is hardly achievable. Instead the pull-out process shows an excellent fit. Both the maximum holding force and the force progression are proficiently calibrated. Figure 7 shows the optimized design of the connector.

Tolerance Analysis

In a connector optimization, the absolute insertion and pull-out forces are important issues. A too low pull-out force, due to given variations, can be life-threatening because of the bare current-carrying components. Thus, the influence of existing tolerances on the pull-out force should be controlled after the optimization.

Therefore, the force curves as well as the maximum insertion force of 100 N and the maximum pull-out force of 150 N are now being investigated in a tolerance analysis. Tolerances can appear along material, load or geometric aspects. In this case, only the tolerances of the 15 opti-

mized geometry parameters are examined with regard to their influence on the two forces and the force curves. For this purpose, an equal Coefficient of Variation (CoV) of 2% and a normal distribution are defined for all 15 geometry parameters. The nominal value of the geometry parameters is the value of the optimal design from the previous direct optimization. These three specifications per geometry parameter must be defined on the input side. The result variable is again the derived force-iteration curve as well as the obtained vectors and the maximum insertion and pull-out force. The same fully parametric 2-D CAD model, like the one already used in ANSYS Workbench, is applied for simulation. The 15 geometry parameters have been defined in the Design of Experiment (100 designs, ALHS). Similar to the sensitivity analysis, the dependencies between the result variables and the input parameters should be clarified.

Table 1 lists some statistical values for the maximum insertion and pull-out force. The minimum and maximum values indicate a large dispersion of both forces around the optimized value (Target Value). At this point, it is appropriate to consider the determination of both a self-selected safety limit and a failure limit in ANSYS optiSlang. Here, the values for these limits are selected exemplarily. The Sigma levels are provided for each limit. There is no specification of a Sigma level to be fulfilled in this case.

Another result visualization is the Box Whisker plot for the maximum insertion and pull-out force (Fig. 8 see next page). The asymmetrical distribution function of both forces can be seen very clearly. The absolute frequency of the violated limits can be counted as well as displayed.

The evaluation of a robust design is carried out with the help of the Coefficient of Variation. If its value for the result variables is smaller than for the input variables, the design can be considered as robust. A look at the CoV in Table 1 of 7% for both result variables compared to the defined CoV of 2% for all input variables, reveals that the design is not robust. The optimum found here is an unstable one. Low input scatter usually causes large output scatter.

In order to identify the most contributing input scatters, the CoP matrix must be analyzed. Figure 9 (see next page) shows the CoP matrix for the insertion and pull-out process as well as for the maximum forces. For the two CoP

matrices in Figure 9, only every second vector component is shown. The CoP-Matrix for both load cases show only 5 input scatter for the insertion process and 6 input scatter for the pull-out process to be significant. Hence, from 15 output geometry scatters, a strong reduction to the most important and less important input scatters could be achieved. For the insertion process as well as for the maximum pull-out force, high total CoPs of less than 96 % are obtained. The pull-out process has total CoPs between 33 - 96%. Again, this is a consequence of the unfavorable geometry definition, which results in partially stepped increases in the pull-out force.

It becomes apparent that in tolerance analysis completely different input parameters are significant compared to the previous sensitivity analysis. This can be explained by the fact that in the sensitivity analysis a large global area is considered, but in tolerance analysis it is just the local area around the determined optimum.

Conclusion

For the examined connector, the sensitivity analysis sufficiently showed the influence of each input parameter in the signal course of the insertion and pull-out process. Due to the partially low CoP values, a direct optimization was performed. By minimizing the deviation between vectors instead of signals, a very adequate fit could be found between the desired and the simulation behavior. However, the subsequent tolerance analysis of the maximum insertion and pull-out force indicated that the optimum is not robust. Nonetheless, the information in the CoP matrix pointed out which input scatters had to be reduced in order to determine a robust design.

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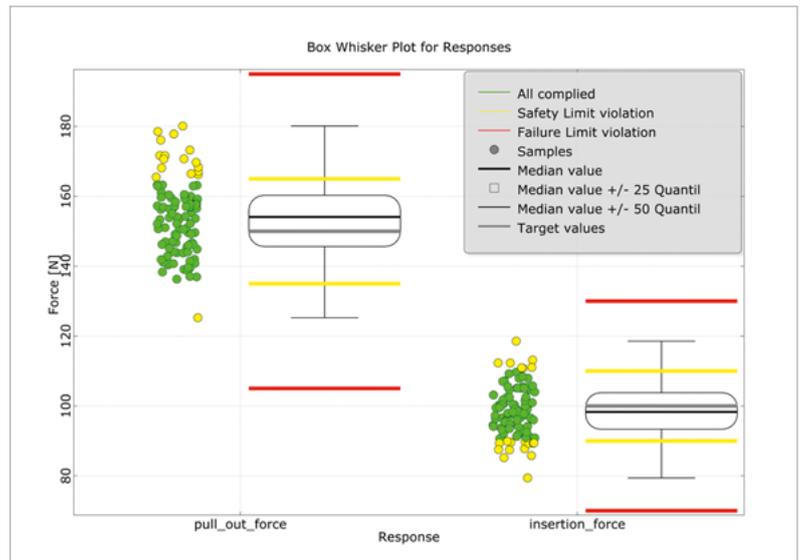


Fig. 8: Box Whisker plot for both result variables, with the grouping of the designs into Safety Limit (yellow line) and Failure Limit (red line)

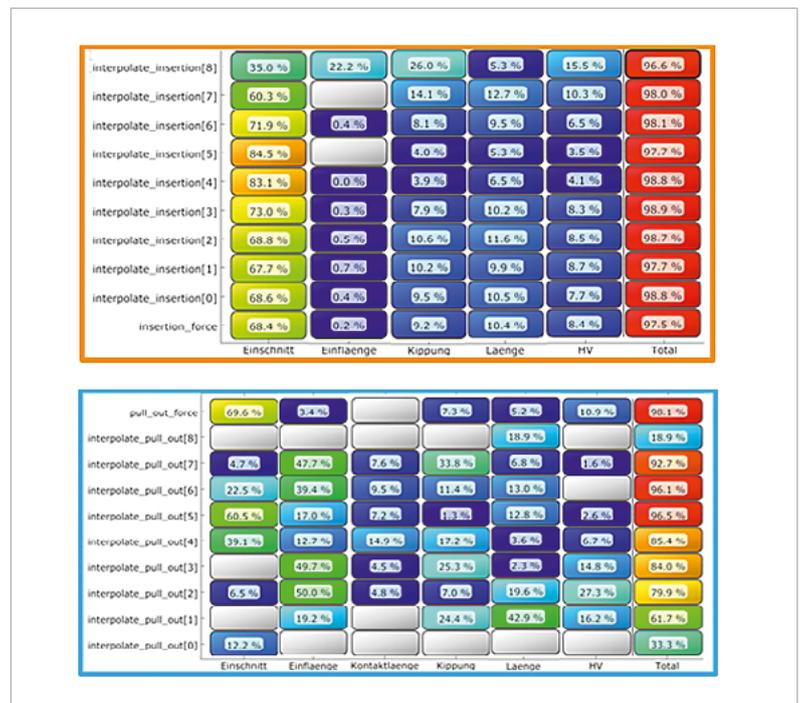


Fig.9: CoP matrix for the interesting marked area of the insertion and pull-out process as a result of the tolerance analysis