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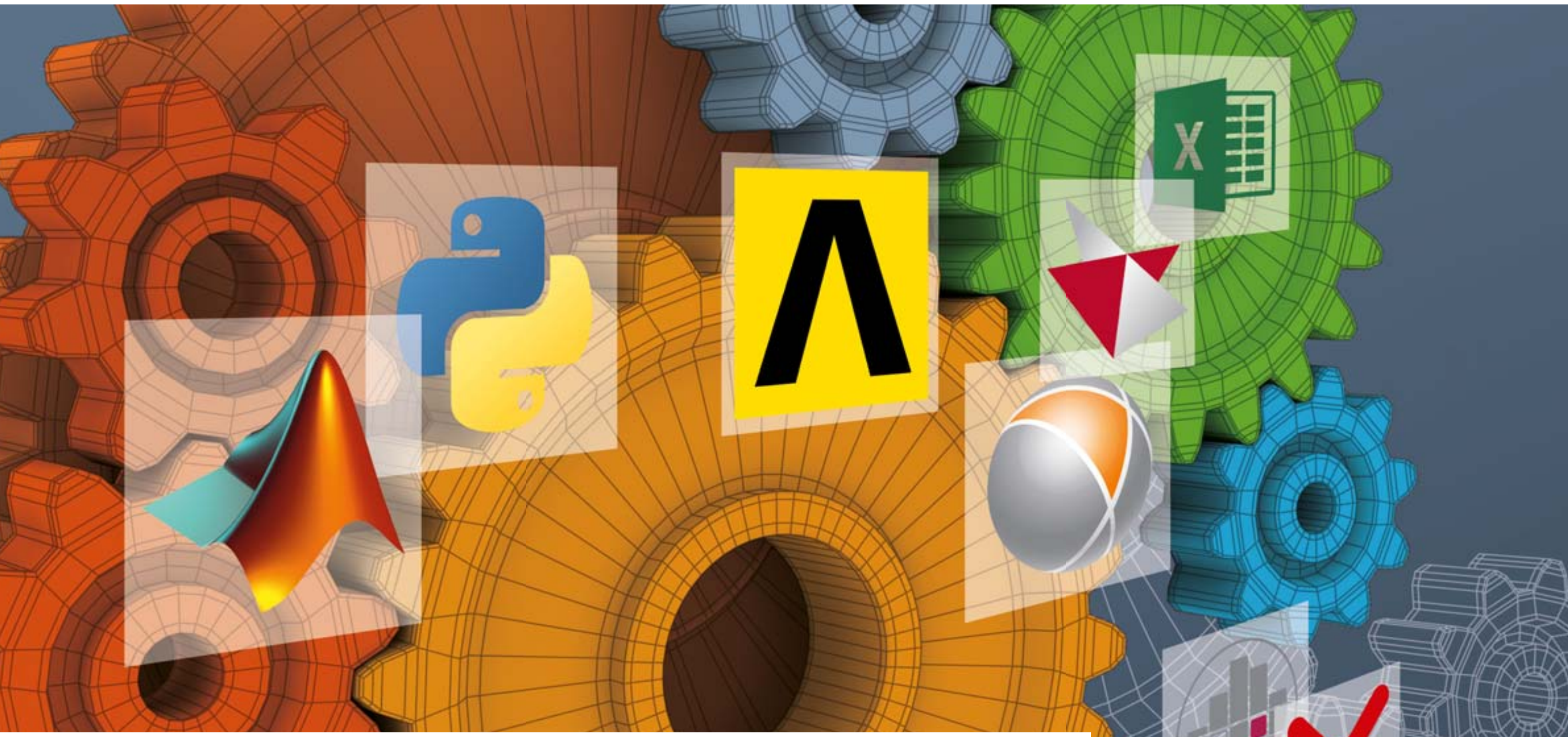

ISSUE 1/2019

Title Story // optiSLang Connects

Individual Optimization of a new 3D-Printed Prosthetic Foot

High-Quality Coriolis Mass Flow-Meters

Light Construction of Power Lathe Chucks

Optimization of a Connector

RDO-JOURNAL

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OPTISLANG CONNECTS

The process of democratization in CAE-based product development means to make analysis tools and results accessible not only to analysts and simulation experts but to all engineers involved in the development process.

So, how can you capture and reuse CAE expertise that it is accessible? How is it possible to embed such knowledge into reusable templates, extending simulation capability throughout the product development team?

optiSLang provides interfacing to almost any software tool used in the Virtual Product Development Process (VPDP) if the requirements to run in batch and to drive parameter variations are fulfilled. The coupling with optiSLang can be automated, either in a single solver process chain or in complex multi-disciplinary and multi-domain workflows. Even performance maps and their appraisal can be part of standardized projects. Via predefined nodes and API Interfaces, optiSLang offers direct access to the parametric modeling of CAE or programming environments like ANSYS ABAQUS, ADAMS, COMSOL, EXCEL, FLOEFD, GT POWER, MATLAB, LS DYNA, MOTOR CAD, NASTRAN, PYTHON, ROCKY, SIEMENS NX, ZEMAX and many more. Users can combine several tools in sequences and iteration loops. For workflow controlling and monitoring, it robustly handles failed designs due to missing licenses, geometries impossible to be meshed or any other inconsistency. All workflows can be stored as reusable templates and made available for the entire VPDP team in PLM or web environments. Of course, the support of different platforms, i.e. Windows, Linux and HPC as well as Cloud computing is provided.

Thus, the entire development team can benefit by capturing the knowledge of each participating member. Every template is a version-controlled building block. It can be used in a modular and flexible way within adaptive projects. While each expert delivers quality assured sub-modules, the whole process becomes standardized. Used tools, algorithms and internal processes can be improved or changed while the entire VPDP is stable and benefits from sub-upgrades.

In this way, optiSLang connects all teams in a collaborative, flexible and standardized workflow for efficient, future-oriented virtual product development.

Apart from that, we again have selected case studies and customer stories concerning CAE-based Robust Design Optimization (RDO) applied in different industries.
I hope you will enjoy reading our magazine.

Yours sincerely

Johannes Will
Managing Director DYNARDO GmbH

Weimar, May 2019

CONTENT

OPTISLANG CONNECTS

optiSLang enables the building of transparent CAE tool chains and combines them with parametric algorithms for a broader usage of CAE techniques.

One of the major challenges of today's CAE engineers is the increasing complexity of processes while results have to be delivered in shorter times. At the same time, within the engineering process, multiple disciplines like NVH, thermal-mechanical-electrical analyses, safety evaluation, tolerance management, cost etc., have to be considered. Improving one discipline could require a compromise in others. Cooperation in multiphysical simulation and multidisciplinary optimization becomes essential for workflows to manage different disciplines and teams.

Simulation Process Management

The daily work of an CAE engineer contains a high percentage of repetitive tasks. Such as reports and result extraction or many parts of model generation. It is also quite common to manually transfer results of one discipline as input into the next step of operation. For example, copying the geometry into a new directory where one starts to mesh it. This also applies for the results of the post processing. Maybe there are Matlab or Python scripts to process the work, sometimes it would mean copy & paste or even retyping into Excel sheets. This procedure is well-known to CAE engineers. Also, customers are aware of how many mistakes might occur during this process. When different variants have to be compared for finding an optimal design, it can lead to an unsorted crowd of data. If simulations are done by different engineers, it can be very hard to compare the results among each other. Thus, many teams or companies started to standardize their working process, resulting in scripting environments with a mixture of Python, VBA, Perl, Bash, Matlab, etc.

optiSLang users run multiple design variants for Robust Design Optimization (RDO) and face the same issues. In the past, engineers had to write scripts to automatize the CAE process. Nowadays, because of multiphysical challenges, CAD and PLM systems, tasks become even more complex. New versions of tools are released every year. All parts of the system need to be connected and maintained. Already several years ago, customers in cooperation with Dynardo realized that a better support of process automation is needed. In order to fulfil this requirement, optiSLang has emerged from an RDO-tool with powerful algorithms to a Process Integration and Design Optimization (PIDO) tool. Thus, the software platform connects tools of customers to automatize their processes of design evaluation. optiSLang

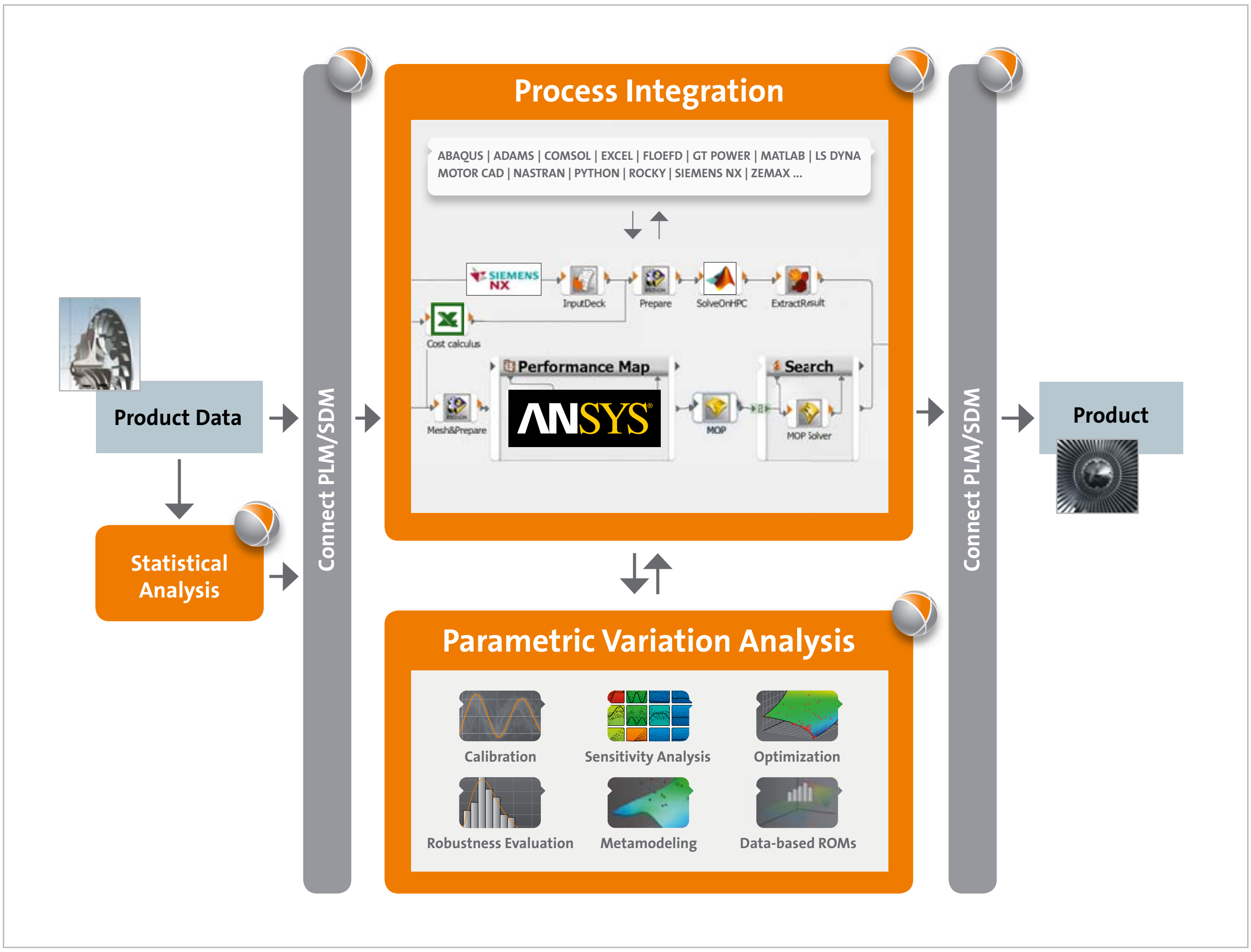

Fig. 1: Simulation Workflow Management with optiSLang

includes interfaces to all major software tools used in the virtual product development. For example, there are integrations of CAD parametric modeling with CATIA, Siemens NX and ProE. CAE parametric modeling is supported by linking ANSYS, ABAQUS, ADAMS, COMSOL, FLOEFD, GT POWER, LS-DYNA, MOTOR CAD, NASTRAN, ROCKY, ZEMAX and many others. Programming environments like EXCEL, MATLAB, PYTHON can also be applied (see Fig. 1). Dynardo established partnerships with many CAE/CAD/PLM vendors to develop and secure the support of these tools.

The coupling with optiSLang can be automated, either in a single solver process chain or in very complex multi-disciplinary and multi-domain workflows. The workflow management allows users to combine several tools in sequences and iteration loops. Conditions, branches or nested loops can be set up graphically. Workflows can be stored as a template project and used again for sub-workflows in a collaborative project. Multiple disciplines can be handled in modular ways to be available in broader systems. This helps connecting different experts and teams.

With optiSLang the overall process is getting much more transparent compared to scripting solutions. As a tool for Simulation Process Management (SPM), it can build and maintain complex tool chains. The modular process integration approach of building programmable nodes provides a very economical way to standardize and automatize CAE workflows. There are many examples of successful projects with Dynardo's customers like Bosch, Daimler, et al.

Example of connecting multiple disciplines

With optiSLang's GUI, a simulation workflow can be built graphically. Therein, any tool can be connected into sequences or put into loops. Figure 2 (see next page) shows such an optimization workflow. The following provides a more detailed insight.

Cost calculation via Excel sheet

In most applications, cost has to be minimized while functional requirements have to be optimized. Therefore, the two disciplines have to be kept in mind and evaluated. Often the cost calculation allows simulations only to be performed if designs are economically valid and if the cost of the design variant is not too high. Thus, expenses and benefits of simulation have to be figured in a balance.

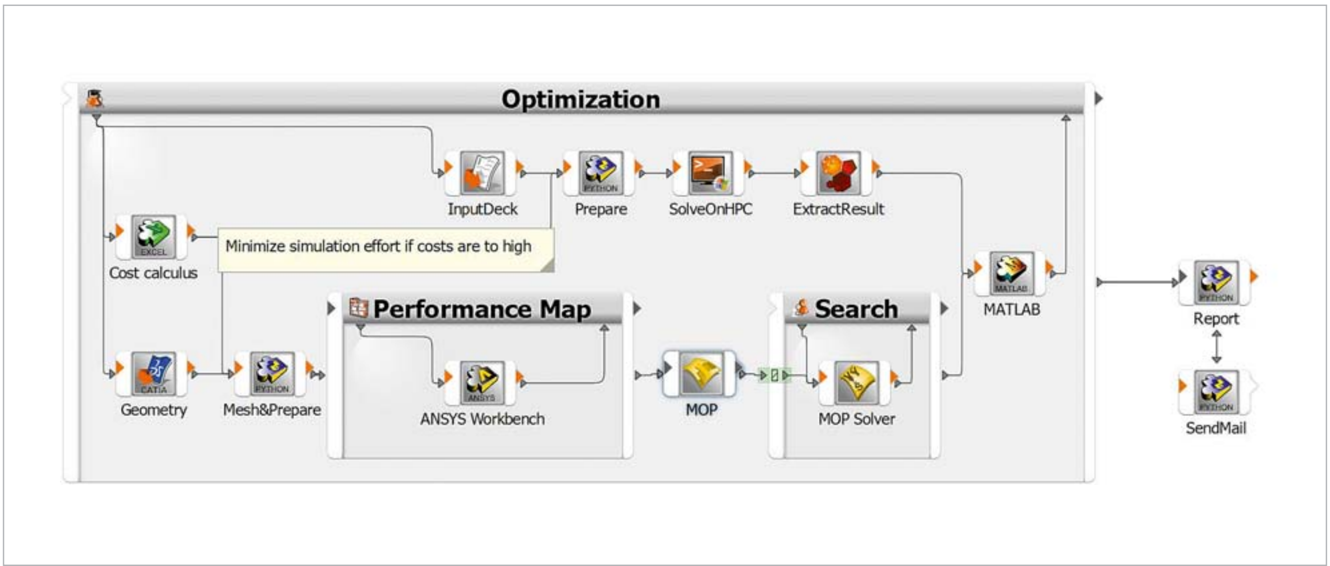

Fig. 2: Optimization workflow in optiSLang considering structural costs and metric of performance map, running several solvers and using HPC

Inhouse code evaluation

This part of the workflow (see upper part Fig.2) starts also with the same parameters like in the excel sheet but, in this case, the calculation takes longer to solve – so it is submitted to a Linux-cluster and runs multiple design points simultaneously. The results are automatically extracted and forwarded to a successive Matlab node.

Load case calculation for given geometry variation

This part (see lower part of Fig. 2) consists of a nested chain, which briefly builds a performance grid for each geometry variation proposed by the optimizer. Therefore, a custom Design of Experiment (DOE) is used. The design points are then forwarded to optiSLang's MOP algorithm for metamodeling. Based on meta-models, the worst loading case for the geometry is searched by optiSLang's optimizer. The worst case scenario is forwarded to the Matlab node.

Post processing

The Matlab node takes the results of 3 prior parts of the workflow and combines them for the optimization task. Additionally, some graphics are automatically produced. All the results are forwarded to the optimizer which can now evaluate them and generate the next iterations until they converge.

If the optimizer finds optimal designs, a report is generated and send via mail. The whole process runs automatically. In this way, the Excel sheet and the CATIA model is updated for each variation. Subsequently, ANSYS Workbench will be started. As additional benefits, optiSLang is capable of handling failed designs and economically controls the maximum runtime of a solver.

Supporting collaborative, flexible and standardized workflows, optiSLang is the platform for efficient, future-oriented CAE-teamwork.

How can CAE expertise be forwarded to other team members?

In the past, there was a relatively small group of CAE engineers with such a high level of expertise to perform key analysis and useful data extraction with tools which were difficult and highly manual to handle. Democratization in CAE-based product development should mean to make analysis tools and results accessible, not only to analysts and advanced simulation experts but also to all engineers involved in the development process. Thus, collaborative work within CAD/CAE teams, which are responsible for different "physics" or disciplines of the product, can share results and processes. optiSLang provides powerful interfaces to publish created RDO and CAE workflows. The power of optiSLang's RDO and Simulation Process Management can be easily integrated into customized platforms.

Example of a collaborative workflow

How such an integration works can be explained using the example of a digital twin. A machine has to be analyzed to figure out when to maintain or repair it. For this reason, sensors are installed. However, this measured data does not provide information how the performance of the machine is effected in the future. Therefore, sensor data has to be combined with 3D-simulation for a continuously updated calibration of important machine parameters. As a result, necessary information can be extracted to optimize maintenance cycles. Fig. 3 shows such a published workflow. The workflow receives the sensor data and calibrates the machine condition. Once this data is available, a condition check can be performed when maintenance will be required. With such a workflow any engineer just has to:

- download the sensor signal
- start the workflow
- forward the results to other team member

To further automate the process, the user defines the workflow

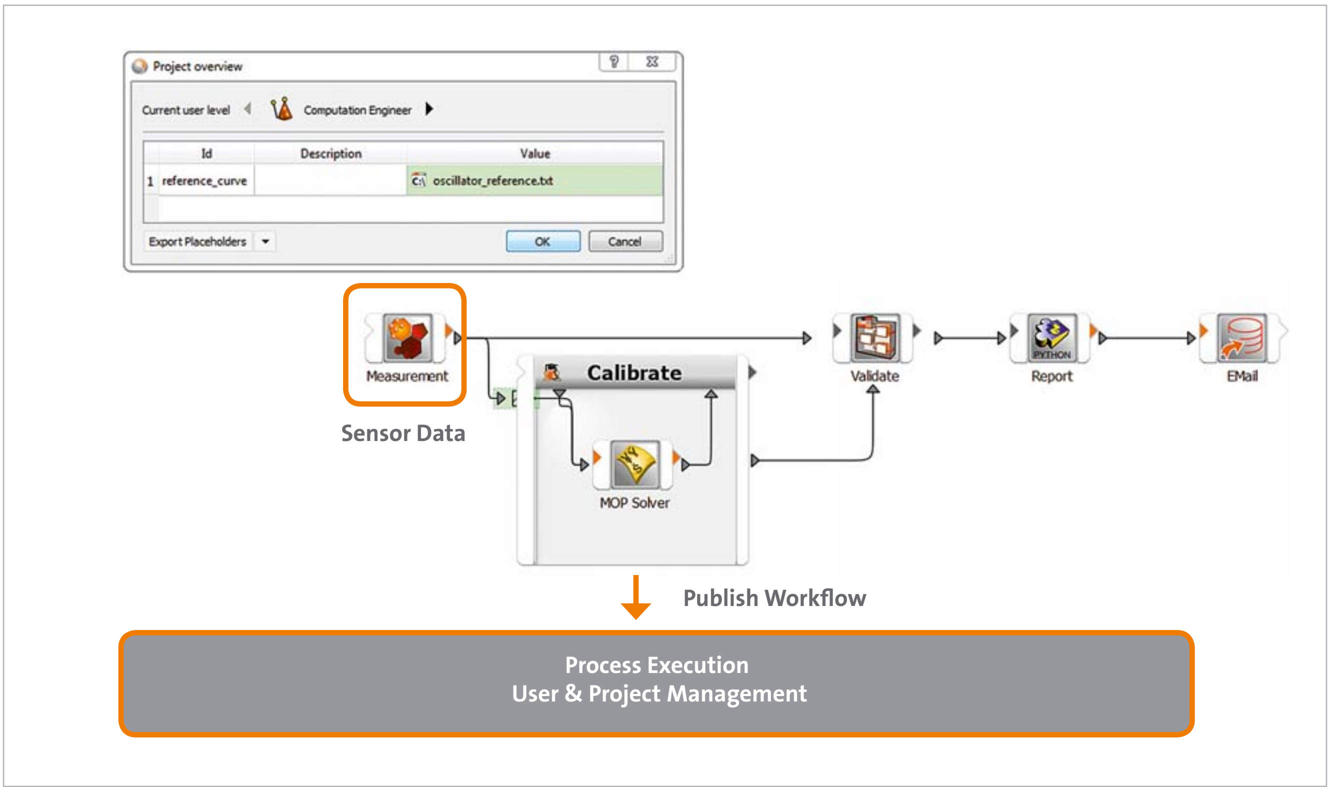

Fig. 3: Digital Twin - Calibration workflow

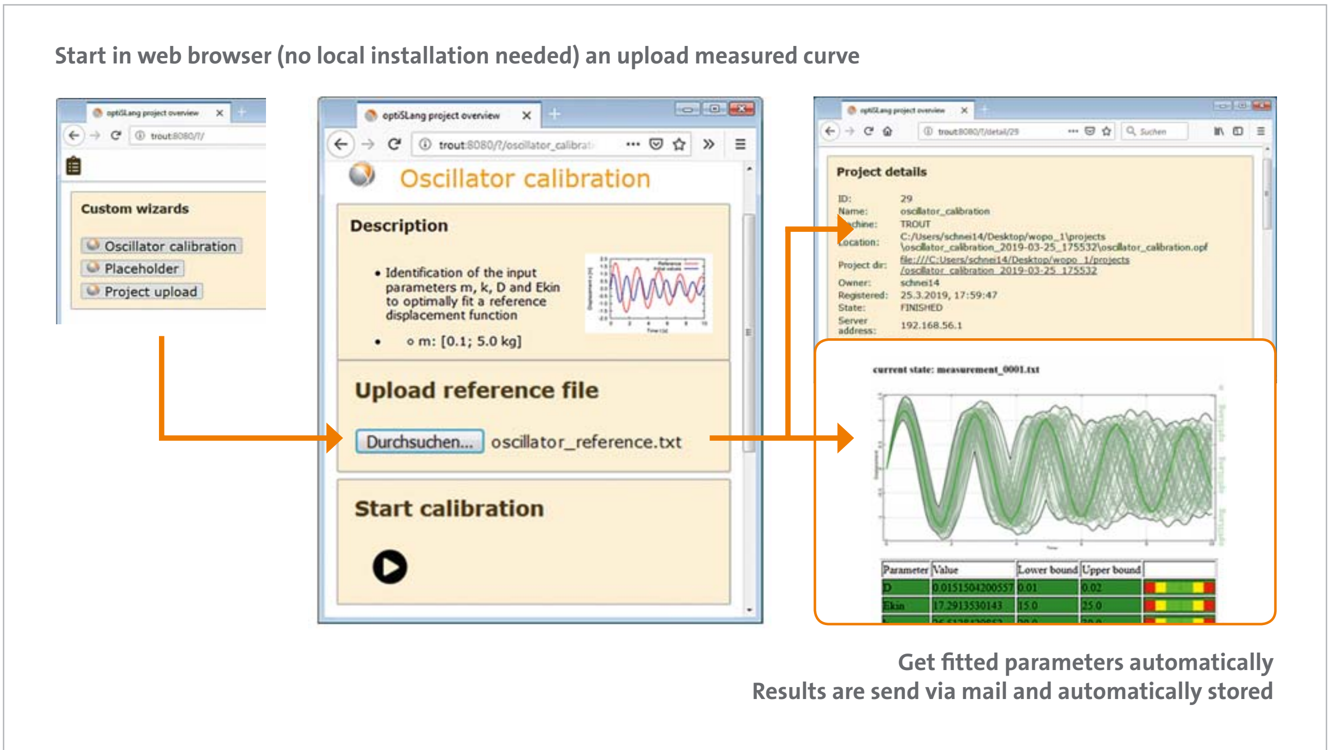

Fig. 4: In-field engineer use calibration workflow

as a template with only the sensor data as a placeholder. Then, the data is uploaded to a Process Execution & Data Management System (see Fig. 3). Every team member can use this procedure in a Process Execution System. In-field engineers just need a browser to have access to all data published in the workflow.

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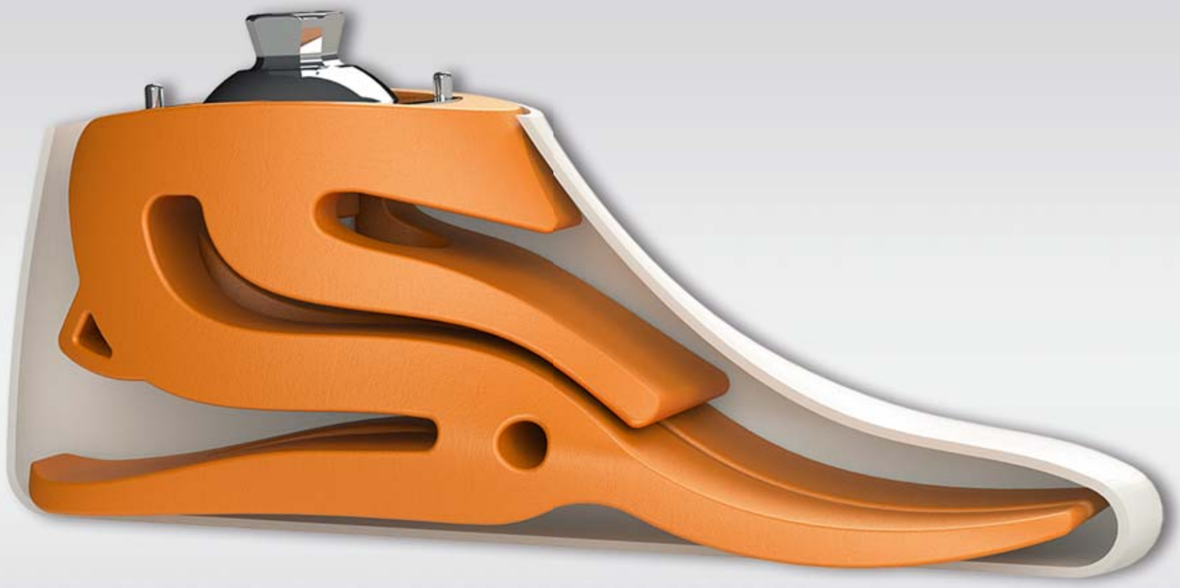

INDIVIDUAL OPTIMIZATION OF A NEW 3D-PRINTED PROSTHETIC FOOT

Mecuris GmbH creates individual prosthetic feet by combining virtual analysis with Additive Manufacturing (AM). optiSLang, ANSYS and Solidworks are applied for parametric simulations.

Introduction

Replacing the functions of a human ankle is challenging as it is an intricate mechanism. Naturally, prosthetic feet aim to mimic the biomechanical characteristics of the intact limb. The design process of such devices is often supported by finite element (FE) simulations to improve their functionality. It is now possible to create individual prosthetic feet by combining virtual analysis with additive manufacturing (AM). By implementing a set of parameters in the design, prosthetics can be adapted to weight and mobility.

For every final prosthetic design, a new evaluation of load and safety would be needed. However, these calculations may be replaced with a comprehensive metamodel to monitor the influence of the specific parameter changes. A robustness study can ensure that the same functionality and safety is provided for each patient.

Vision

At Mecuris GmbH, we aim to supply each patient with an individual aid (see Fig. 1). Therefore, throughout the design process of prosthetics and orthotics, we have to make sure that patients and orthopedic technicians are involved in the development of the final product. This influence provides individual performance and aesthetics considering certain safety boundaries.

Selective Laser Sintering (SLS) has significantly improved in the past few years, and now allows the production of highly durable products. Prosthetic feet have to withstand a fatigue test (2 million load cycles) to be certified. Furthermore, AM allows great geometric freedom, such that adjustments of geometric parameters in the CAD model can be realized in manufacturing.

Development and Testing

The development of prosthetic feet at Mecuris GmbH is carried out considering a single size and body weight. Naturally, when these patient parameters change, the function and safety of the aid deviates.

A few ISO norms can characterize prosthetic feet, including ISO 10328, which contains the previously mentioned durability test for critical heel and toe loading. Other norms aim to simulate a gait cycle on a test bench to provide deeper functional understanding.

Fig. 1: Patient fitting and rehabilitation with a 3D-printed Mecuris prosthetic foot. The foot displayed is inserted into a cosmetic shell

FE-simulations can model the ISO 10328 with reasonable complexity and computational time. Still, the parametric FE-simulation of two different load cases poses challenges.

A combination of physical and virtual testing facilitates the development of a safe and well-functioning prosthetic foot.

Particularly important is the rollover-shape (ROS) of the design that determines how smooth the patient walks and is closely linked to other performance parameters. FE-simulation of the ISO 10328 (see Fig. 2.) load cases can predict the ROS, with significantly less computational effort than the FE-simulation of the whole gait cycle.

Metamodels

Once the prototype fulfills most design requirements, a broader parametric study is necessary to evaluate parameter adjustments from safety (certification) and functionality aspects. The study presented in this paper considered so-called patient parameters (size, bodyweight) and free parameters (three geometric values). The patient's influence reflected in the patient parameters and the free parameters were used in the optimization.

Firstly, the parameter ranges were defined and implemented in a robust parametric CAD model. The parametric model was built up using Solidworks Professional 2017. The next step involved an automatic FE-simulation setup applying "named selections" to maintain references. We used ANSYS Workbench 19.2 as an FE-solver in this study. In the FE-model of the physical test bench, non-linear contacts and plasticity were considered. The Design of Experiments (DoE) was further complicated by creating stable references in the FE-simulation, dealing with meshing and convergence problems.

The design sampling was carried out with the optiSLang 7.2 add-in in the ANSYS Workbench environment. Advanced Latin Hypercube Sampling with 50 and 150 design points were used for heel and toe loading respectively. Besides the previously mentioned five inputs, 3 functional and 11 safety outputs were defined (total). The approximation quality of the metamodels reached a Coefficient of Prognosis (CoP) value of 95% or more in most cases.

Fig. 2: ISO 10328 test stand and modeling of the two load cases with the subject prosthetic foot. All construction components are included in the FE-simulation (equivalent stress is shown)

Promisingly, the free parameters had a high influence on the outputs, indicating that functional adaptation is possible. For example, heel thickness influenced 46% of the heel deformation at heel loading (heel strike) and body weight was only the second most important parameter with a CoP of 36% (see Fig. 3).

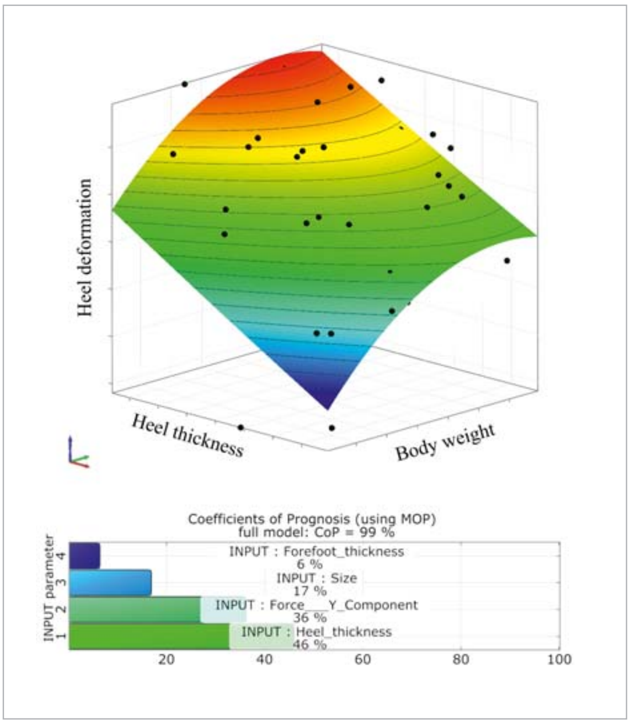

Fig. 3: Metamodel of Optimal Prognosis for Heel Deformation. The model shows high accuracy with only roughly 50 design points

Functional Robustness

Traditionally, robustness is associated with manufacturing imperfections. However, in this study, we sought to achieve a parametric design that allows functional adaptation based on patient parameters. This was not possible with only one robust design, since both patient parameters (foot size and bodyweight) range widely and their distribution was unknown due to lacking broad data.

Therefore, a new idea was necessary: to set certain safety limits, and optimize the free parameters for each size-body weight combination in the restricted domain. The optimization aimed to replicate the functional parameter values of the already existing reference design. This was reflected in a single combined objective function, since manual multi-objective optimization in each case would be too time-consuming. To perform these optimization tasks, we switched to optiSLang 7.2 standalone, where the already available metamodels were imported. Figure 4 shows the optimization system setup.

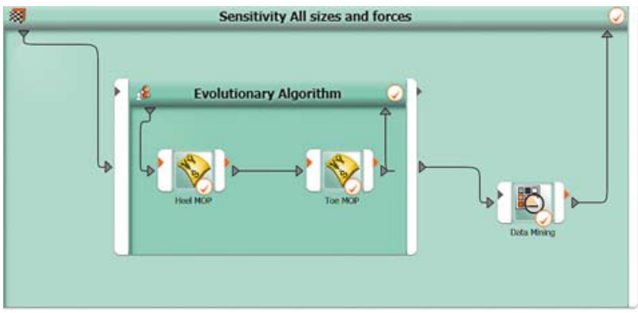

Figure 4: A nested system where the inner optimizer adjusts the free parameters and the outer sampling system changes the patient parameters. An evolutionary algorithm is used to approximate the global optima

The optimized designs closely followed the prescribed functional parameter values. However, the prediction of a full ROS with only two load cases raised difficulties, even when a fully-developed reference existed.

Therefore, functional validation of three optimized designs with varying patient parameters was carried out. We used a previously developed FE-simulation tool which provides the full ROS of the prosthetic foot. The comparison of three validation designs to the reference design revealed similar (promising) ROS performance for all designs (see Fig. 5).

In conclusion, the prosthetic foot developed for a single patient was extended to a range of patients using freely adjustable geometric parameters. The means of this adaptation included modeling the two load cases of the ISO 10328 standard, performing a design study with these FE-simulations, and optimization on the metamodels. The idea of additively manufacturing prosthetic feet allowed to replace the traditional robustness evaluation with a patient-specific optimization, thus reaching the ideal functionality in each design.

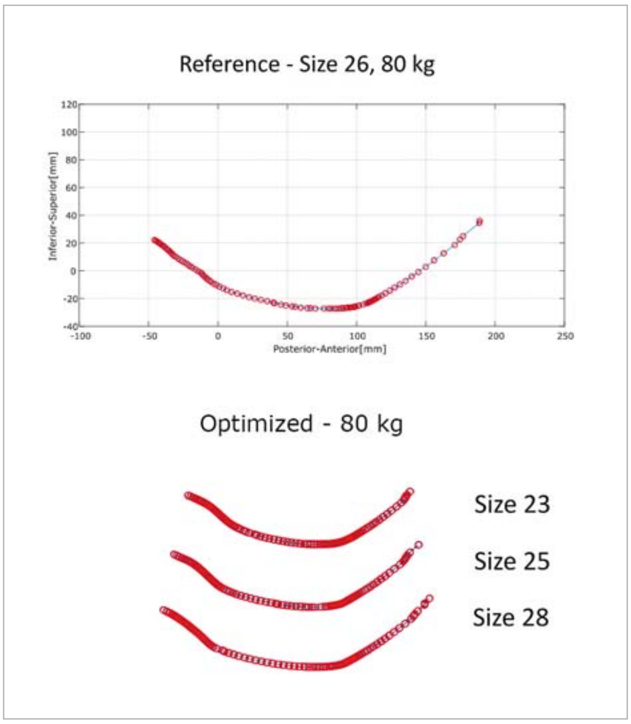

Figure 5: The rollover-shapes of the reference design and three optimized designs for the same body weight but varying foot sizes

Optimization time

The computation of the two design studies (heel and toe loading) lasted roughly 3 and 7 days respectively. The computer used for the calculation was equipped with 8 cores and 16 GB RAM. The optimization time for all size-body weight combinations (56 cases) lasted roughly 2 hours. This calculation only has to be performed once, and later the optimized free parameters can be picked for the given patient data.

User Testimonial

Patient testing and feedback are essential for prosthetic foot development. Our testimonial received two variants of the product to evaluate different daily use cases.

We designed and manufactured two versions, one for Nordic Walking and another for performing domestic chores (e. g. carrying heavy objects). These activities require different functional properties from the prosthetic foot. In the first case, we allowed more flexibility and a smooth rollover-shape. For the second purpose we optimized the foot for an increased body weight, taking the extra load into consideration.

"The prosthetic knee harmonizes well with both feet. [...] One foot is a soft variant for usage at home, the other is a stiff variant for outdoor usage and fast walking. My subjective impression confirms the different behavior of the feet."

Michael Kramer, Rehatreff, 1 | 2019 (translated from German)

Outlook

All simulation models in this study were validated against physical measurements for the reference design and proved to be accurate. Thus, the most significant question for this optimization tool appears in quantifying patient preferences that can serve as input for the optimization objective.

Additionally, further improvements of the metamodels are possible by exploring more design points or making mesh refinements to avoid noisy results. Moreover, the ROS FE-simulation setup that validated the optimized designs might be directly used for the DoE. It can provide deeper understanding of functionality but it raises computational effort significantly.

There is a German patent pending of the prosthetic foot with the number: DE 10 2019 100 584.1

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HIGH-QUALITY CORIOLIS MASS FLOW-METERS

The Promass Q is an awarded product from Endress+Hauser. The innovation was achieved by using an experimental set-up complemented by simulation methods of ANSYS Workbench and optiSLang.

Endress+Hauser Group

The Endress+Hauser Group is a leading supplier of measuring instruments, services and solutions for industrial process engineering. Endress+Hauser provides sensors, devices, systems and services for level, flow, pressure and temperature measurement as well as analysis and measurement logging. The company supports its customers with automation, logistics and information technology services and solutions. The products are setting standards in terms of quality and technology.

Coriolis Effect allows accurate measurement

Multivariable sensor technology and maximum measuring accuracy are only two reasons why gases and liquids are increasingly captured with the Coriolis measuring principle.

The Coriolis mass flow-meter is an outstanding product from Endress+Hauser's wide range of products. This measuring instrument is inserted into a process line and continuously detects the parameters of the fluid flowing through it (see title image and Fig. 1). In addition to the mass flow rate (±0.05%), this instrument also tracks the density (±0.2 kg/m³) and the temperature (±0.1°C) with extraordinarily high accuracy. The Coriolis Effect is used to directly determine the mass flow rate. For this purpose, the measuring tubes located between the process connections are resonated by an activator (Fig. 2). If a fluid now flows through the measuring tubes oscillating in the opposite direction, the tubes begin to tumble due to the Coriolis force. This movement is picked up by two sensors at the inlet and outlet of the measuring tubes. A signal processor calculates the phase difference between these two signals, which is directly proportional to the mass flow. In addition, the fluid density can be derived from the resonance frequency, and finally the fluid temperature is measured precisely by a temperature sensor on the measuring tube.

Sensitivity Analysis, Optimization and FEM Simulation with optiSLang and ANSYS

The decisive factor for the reliability and measuring accuracy in practice is the non-dispersion of the measuring tube vibrations into the connected process line. The process connection must stand still at all fluid densities. High-quality Coriolis mass flow-meters are therefore always "in

Fig. 1: Coriolis mass flow-meter Promass Q

balance", which results in outstanding measuring accuracy. Usually, the principle of the tuning fork is used, whereby the flow is divided between two pipes oscillating in opposite phases (Fig. 2). Both, this balance and the insensitivity of the measuring tube vibration towards changes in process values (temperature and pressure) and material properties (density, viscosity and sound velocity) were optimized with ANSYS Workbench and optiSLang. This optimization is based on parameters, implemented in the ANSYS programming language APDL, which reflect the properties of the measuring instrument relevant to practice. The search for a robust and optimal compromise between often conflicting design goals was realized with optiSLang.

Fig. 2: Fundamental oscillation of the measuring tubes at about 100 Hz and a few micrometers of deflection (shown in heightened form).

An engineering preselection resulted in a sum of approximately 100 relevant geometric parameters as well as numerous objective values for the optimization problem. Then, sensitivity analyses were performed with ANSYS optiSLang. On this basis, the relevant geometric optimization parameters were identified and preliminary decisions were made regarding the most important objectives and criteria (Fig. 3). In this case, a ranking of several targets in the objective function was sufficient, since no serious conflicts arose. This reduced the number to 10 key criteria. Taking geometric constraints into account, such as the avoidance of component collisions, the assurance of production-ready geometries or the consistency of component shapes, optimal and robust design layouts could be found quickly and purposefully.

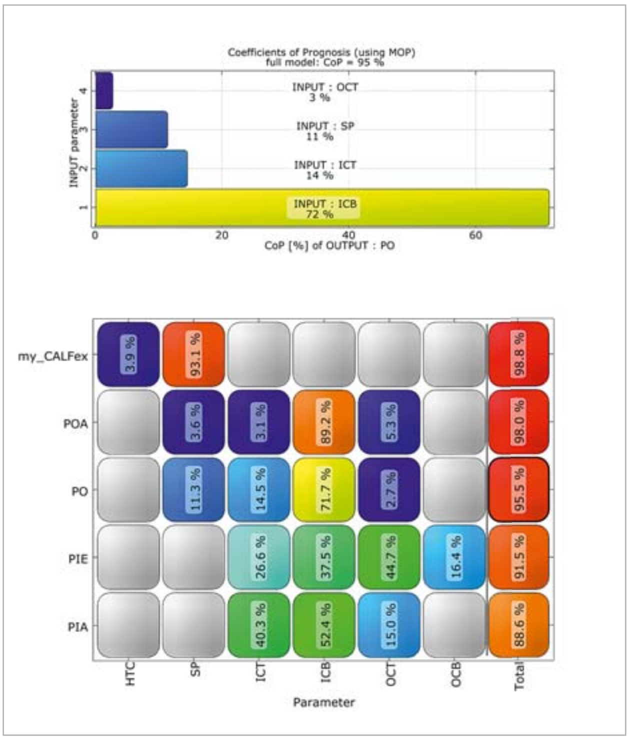

Fig. 3: Illustration of CoP Plott with objective function.

In order not to lose the correspondence to reality, it is helpful to build bridges as often as possible between the realized prototypes on the one hand and the FEM simulation on the other hand. The thereby related synchronization of the material parameters is the basis for an exact prediction of the real system behavior by simulation. As a result of this procedure, out of the FEM simulation a better understanding of the functional principle of the measuring device is gained. Using ANSYS Workbench, experimentally observed phenomena can be reproduced on the computer and can also often be understood, which contributes significantly to the development of solutions. With the aid of simulation, many costly and time-consuming experiments can be omitted in this phase.

Until now, high measurement accuracy was only possible under ideal conditions, in other words under stable process conditions as well as under single-phase and homogeneous media that follow the pipe vibration without any restrictions. In practice, however, such ideal conditions often do not exist. Food - for example ice cream or cream cheese - is deliberately foamed. However, gas often also emerges unwanted from media such as mineral oil, which cannot be removed due to its high viscosity. Promass Q (Title and Fig. 1 see previous page) is a Coriolis flowmeter that has been developed especially for applications in the oil, gas and food industries.

Active Real-Time Compensation of Measurement Errors

Gas bubbles enclosed in the medium reduce the fluids ability to follow the tube motion, resulting in considerable measurement errors. Thanks to revolutionary “multi-frequency technology” (MFT), active real-time compensation of these measurement errors is possible. For this purpose, the measuring tubes are stimulated simultaneously with a fundamental and a harmonic component (Fig. 4). This harmonic component now provides the missing information to determine a system of equations and a reliable correction algorithm. When the fluid density changes, the fundamental as well as the harmonic component cover wide frequency bands. With the help of ANSYS Workbench, first interfering resonances in these frequency bands can be detected and second measures can be defined to shift these resonances out of the frequency bands. In Promass Q, 15 patents were implemented, and during the six-year development and industrialization phase, approximately 1,000,000 virtual prototypes were generated. The innovative “multi-frequency technology” was honored with, among others, the “Swiss Technology Award” and the “German Innovation Award” (Fig. 1 see previous page). Complex vibration-capable systems such as Promass Q would be impossible without numerical simulation. Within the development of modern process sensors it is no longer feasible to imagine prototyping without a combined approach using experimental set-up supported by simulation methods. In this process, ANSYS Workbench in combination with optiSLang has proven to be a powerful instrument. Endress+Hauser has been using simulation tools from ANSYS for more than 25 years.

Fig. 4: Harmonic component at about 1000 Hz (deflection shown in heightened form)

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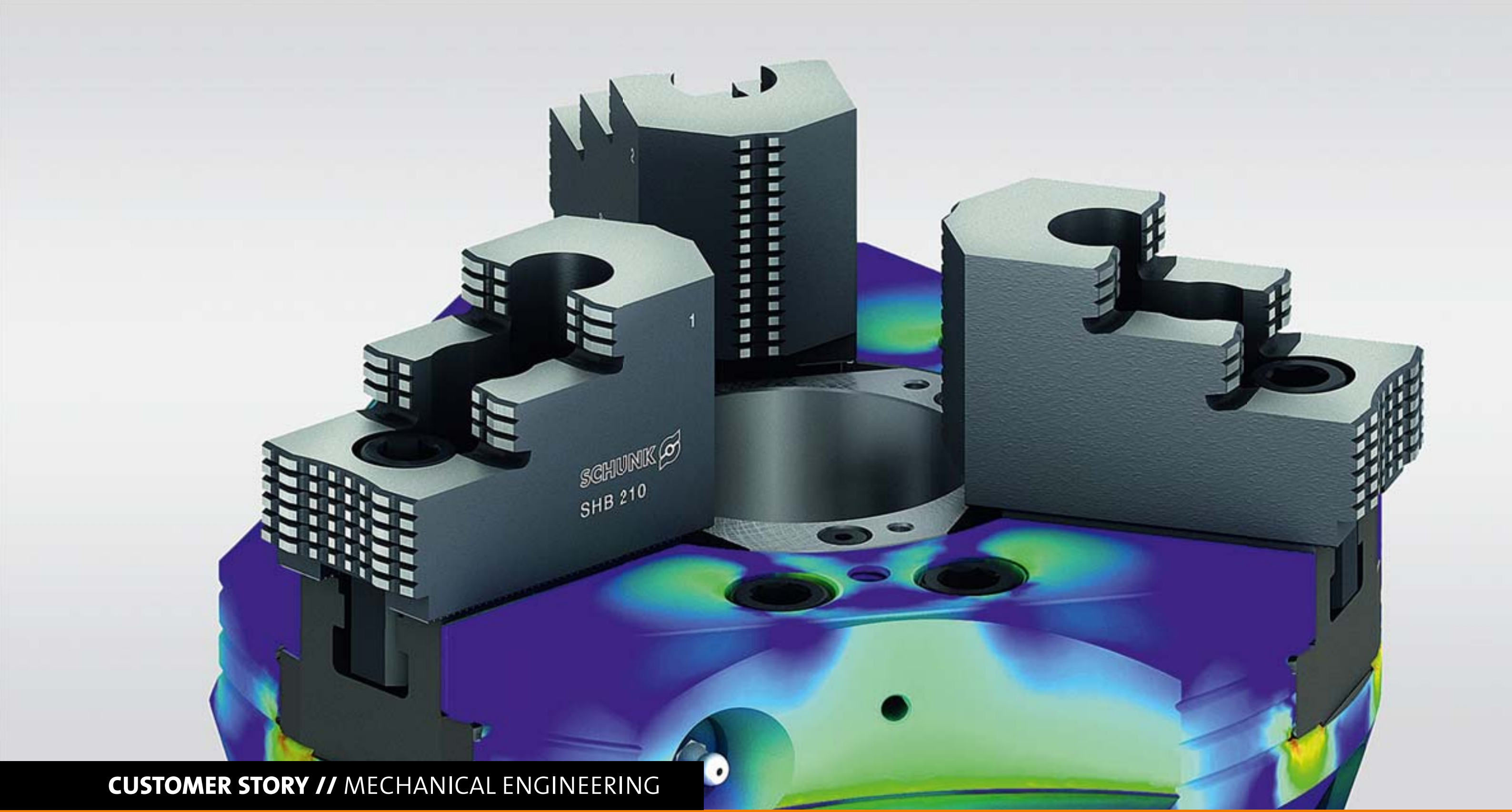
This article was adapted from an article published in the CADFEM Journal 2-2018.



CUSTOMER STORY // MECHANICAL ENGINEERING

LIGHT CONSTRUCTION OF POWER LATHE CHUCKS

While aiming at lighter chucks for lathes, SCHUNK meets the requirements of customers for quick and energy-efficient component production. For this purpose, SCHUNK uses ANSYS simulation solutions including optiSLang for topology and parameter optimization.

SCHUNK's wedge hook power chuck ROTA NCE combines lightweight construction, maximum load capacity and innovative design. The lathe chuck was geometrically adapted to the power flow for providing maximum stiffness as well as lightweight requirements. Compared to conventional lathe chucks and depending on the size, the mass inertia could be reduced by up to 40 percent.

High Stiffness at Low Mass

The aim of the specialists at SCHUNK competence center for turning technology and stationary workholding in Mengen was the improvement of the energy management in accordance with DIN EN ISO 50001. They wanted to develop a clamping device with low mass or mass inertia in order to minimize the energy and duration required for acceleration. However, the basic clamping function of the chuck - measured in terms of stiffness and variability - should be fully maintained, if possible even increased. Also the desired radial and axial run-out accuracy had to be guaranteed.

In this case, the rough structure of the clamping device components was determined with topology optimization on the basis of the respective force flow. Using the resulting parameter optimization, dimensions were then varied to identify an optimal geometrical structure. For final optimization, e.g. of the jaw guidance, a suitable geometric parameterization is important, since the topology optimization does not allow a detailed depiction of the contact areas. In parameter optimization, lift-off and non-linear contacts of the entire chuck assembly can also be modeled and simulated. The properties of the optimized clamping device could be subsequently evaluated by FE analyses and compared with the previously manufactured designs.

Arched Structures Below the Jaws

"In ANSYS, we defined an initial model for topology optimization including the necessary constraints such as forces and bearings," explains Mathias Siber, who used the project for his master's thesis. "The objective function of the optimization was the maximization of the stiffness, with mass restriction at 70, 50, and 30 percent of the initial mass." In addition, the existing functional areas were marked to exclude them from optimization (non-design areas) because they should remain in their original shape. The optimization algorithm then determined the basic geometrical shape

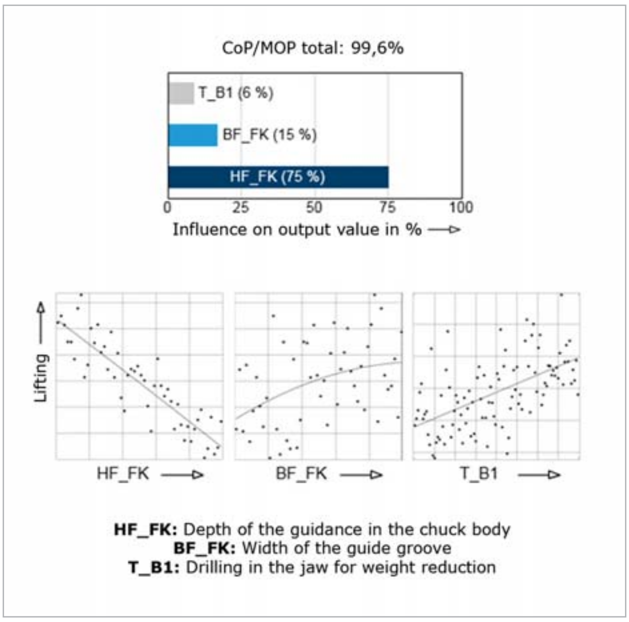


Fig. 1: Influence on lifting indicated by COP/MOP measures

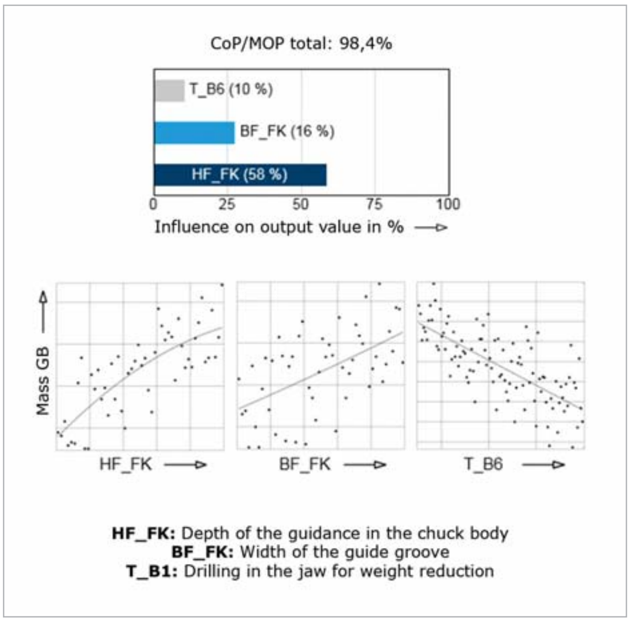


Fig. 2: Influence on chuck mass indicated by COP/MOP measures

according to the mechanical loads and specified mass restrictions. In the chuck body, arched structures below the jaw guide, circular recesses between the guideways and an overall conical chuck contour were created.
"The topology optimization significantly reduced the weight of the lathe chuck, which also has a positive effect regarding the load on the spindle bearings", stated Philipp Schräder, Head of Development Clamping Technology. "In addition, we registered the vault structure resulting from the topology optimization as a design patent at the German Patent and Trademark Office in order to protect it as far as possible from unauthorized copying."

Sensitivity Studies Show Influence of Parameters

After topology optimization, parameter optimization was performed on the reconstructed parametric geometry model using sensitivity studies conducted with optiSLang from Dynardo. Thus, the influence of input parameters on the desired output data could be investigated, visualized and evaluated. The subsequently used optimization algorithm searched for the minimum of the correspondingly defined target function, including the reduction of lifting even at high clamping forces. In addition to the chuck body, base and top jaws were also included in the procedure.

"Using optiSLang we could figure out how the jaw guidance should look like", Mathias Siber explains. "We analyzed which parameter changes would lead to the desired result of little deformation at low weight." Regarding the base jaw, mass and axial lifting were critical. Here, the parameters "depth of the guidance in the chuck body" and "width of the guidance groove" dominated. The depth of the guidance showed opposite effects, because the deeper the guidance in the chuck body, the lower the lifting effect. On the other hand, the mass of the base jaw increases proportionally.

Multi-Objective Optimization Facilitates the Design Process

In this case, parameters are optimized towards the objective of less lifting at the lowest base jaw mass. The result of this multi-objective optimization is an optimal depth-width ratio of 2:3 for the base jaw guidance. This allows a very precise examination of the product behavior with different geometries in order to create a "robust" design. The robustness of the final design was ensured by means of suitable constraints.

While the topology optimization identified the lightest chuck design from the force flow, the parameter optimization ensured maximum stiffness and reduced notch stresses for the longest possible chuck life. In addition, a numerical stress analysis was conducted according to FKM guidelines.

The Prototype Meets All Requirements

After optimization, prototypes of each chuck size were produced. Afterwards, they were examined and verified on a test bench with up to 500,000 cycles, which took several months. "Similar to other projects and due to the profound simulation during development, only one prototype per size was required to fully meet the specified requirements", emphasizes Philipp Schräder. "Since a prototype test can take several months, for a new development the time saved by the simulation is approximately half a year."
Topology and parameter optimization made a lightweight chuck possible where the mass was reduced by 30 percent and the mass inertia by 40 percent. A 20 percent lower jaw centrifugal mass caused advantages such as shorter acceleration phases and a lower loss in clamping force under rotational speed. By optimizing the parameters in the jaw guidance area, the chuck stiffness was increased while the stress level was reduced at the same time. The result was

Fig. 3: FE topology optimization identifies the lightest chuck design from the force flow

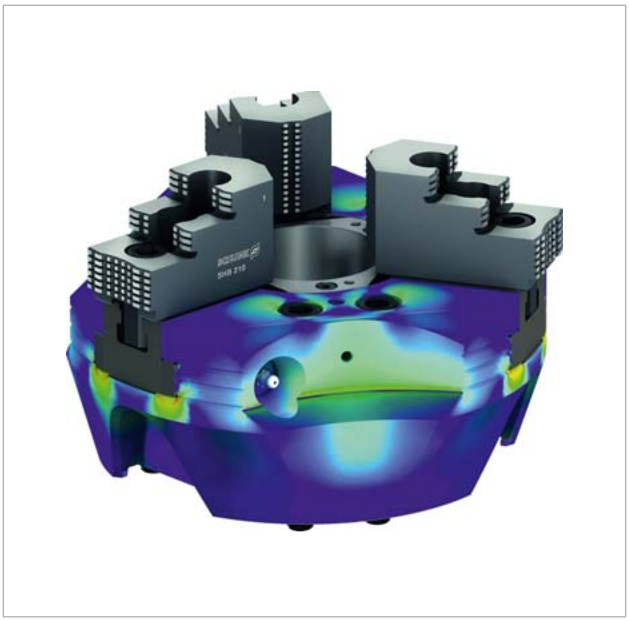


Fig. 4: FE parameter optimization for reduced notch stresses and highest stiffness

Fig. 5: Result of the optimization process – ROTA NCE

Fig. 6: The axially displaceable piston transmits the force to the base jaws and generates a radial jaw movement synchronous to the axis of rotation

a 20 percent increase of the maximum bearable clamping force. In combination with the reduced jaw centrifugal mass, a possible speed increase of 10 percent could be achieved. By reducing the time for testing combined with a stress calculation according to the FKM guideline and depending on the sizes, a cost reduction of approx. 30% could be reached in the development. As a result, the SCHUNK ROTA NCE lathe chuck provides the user with ideal conditions for high process dynamics and productivity while using a minimum of energy. Particularly in large-scale production, the energy- and cycle-time efficiency of the chuck leads to significant savings and fulfills the DIN EN ISO 50001 energy management certification.

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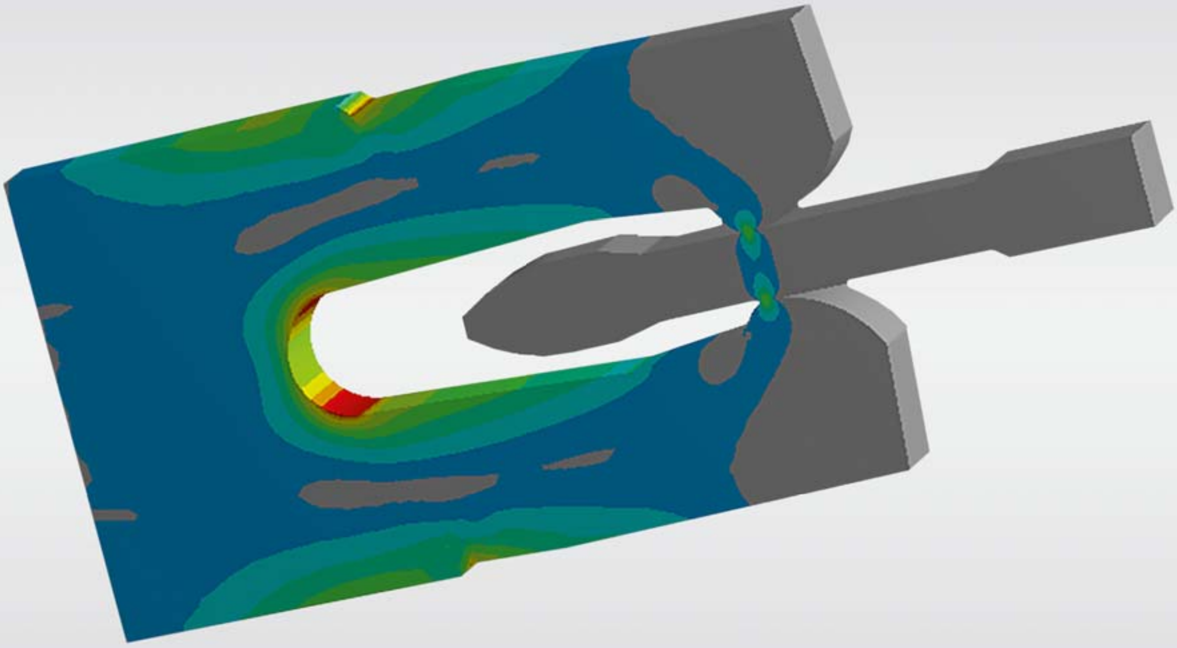

CASE STUDY // ELECTRICAL ENGINEERING

OPTIMIZATION OF A CONNECTOR

Wit 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

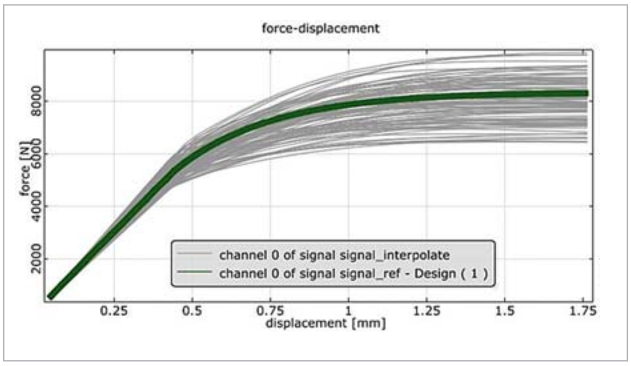

Fig. 1: Force-displacement curve from sensitivity analysis (grey) in comparison to the reference curve (green) of the tensile test

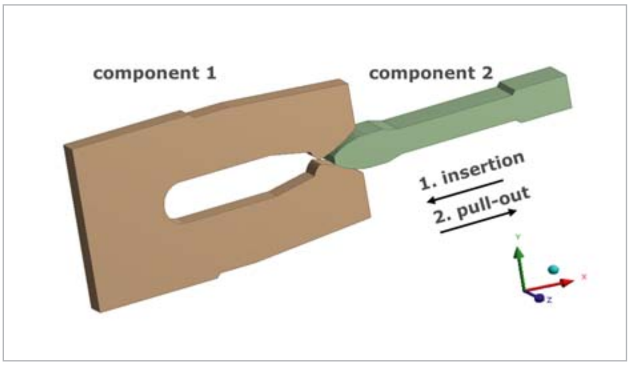

Fig. 3: Simplified parametric model of a connector with the current-carrying components without plastic components

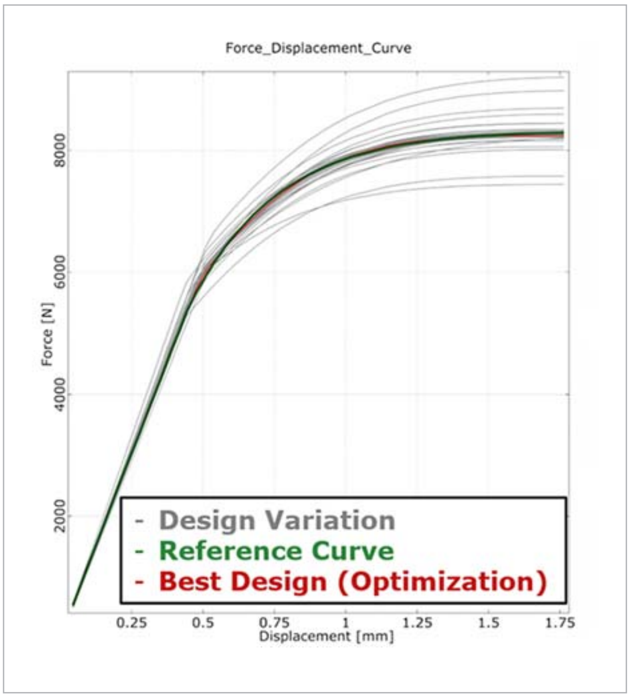

Fig. 2: Force-displacement curve of the optimum (red) compared to the reference curve of a tensile test (green) and the other curves obtained from the optimization (grey)

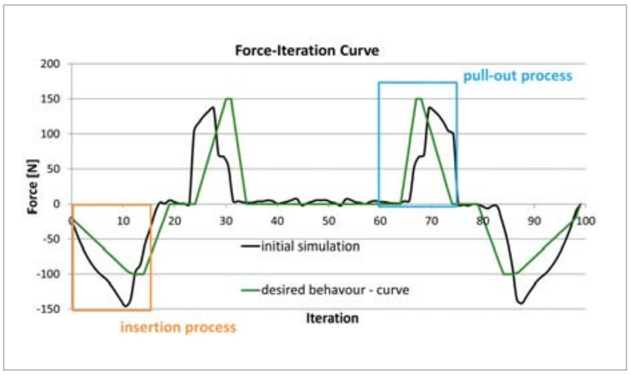

Fig. 4: Force-iteration-course of the reference curve (green) and of the initial design (black) of a connector with marked areas for insertion and pull-out process

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. 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-

Name	Type	Expression	Criterion
objective	Objective	euklidnorm(vector_insertion_ref-vector_insertion)+euklidnorm(vector_pull_out_ref-vector_pull_out)	MIN

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

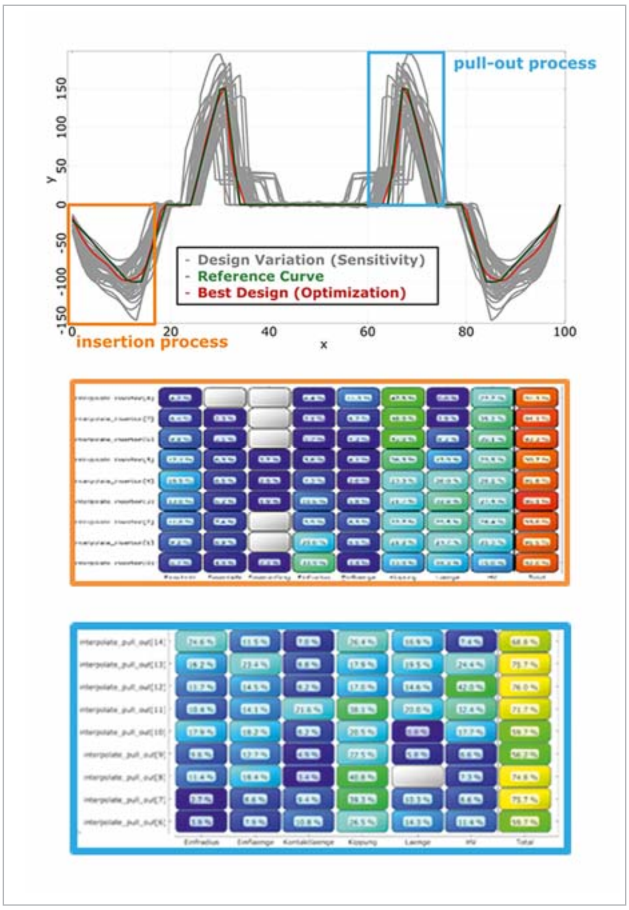

Fig. 6: Variation of the force time curves from the sensitivity analysis (grey) compared to the reference curve (green) and to the optimal design (red) from the direct optimization with the CoP matrix for the important marked area of the insertion and pull-out process as a result of the sensitivity analysis.

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-

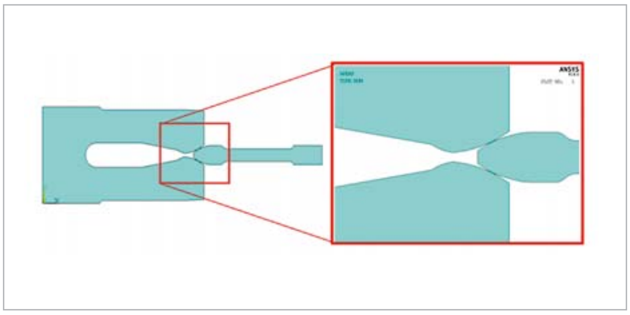

Fig. 7: Representation of the connector geometry for the optimum design from the direct optimization, with a detail of the contact zone

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 optimized 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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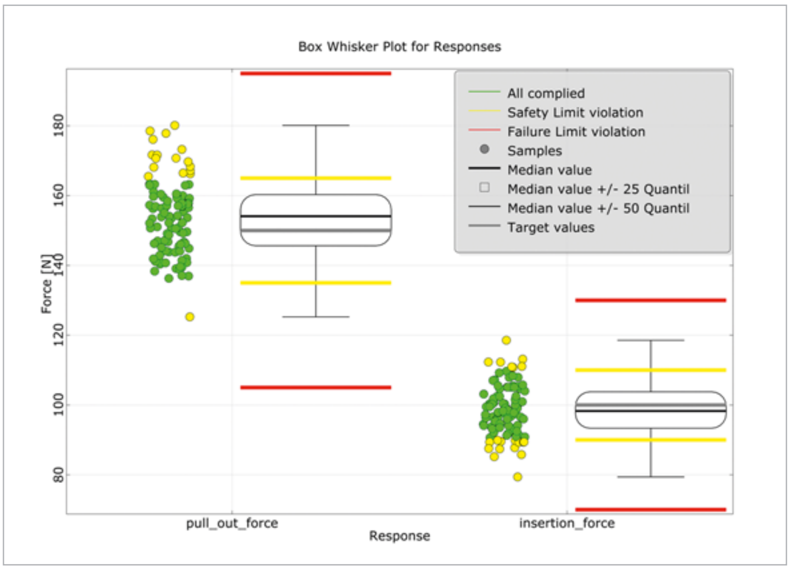

Fig. 8: Box Whisker plot for both result variables, with the grouping of the designs into Safety Limit (yellow line) and Failure Limit (red line)

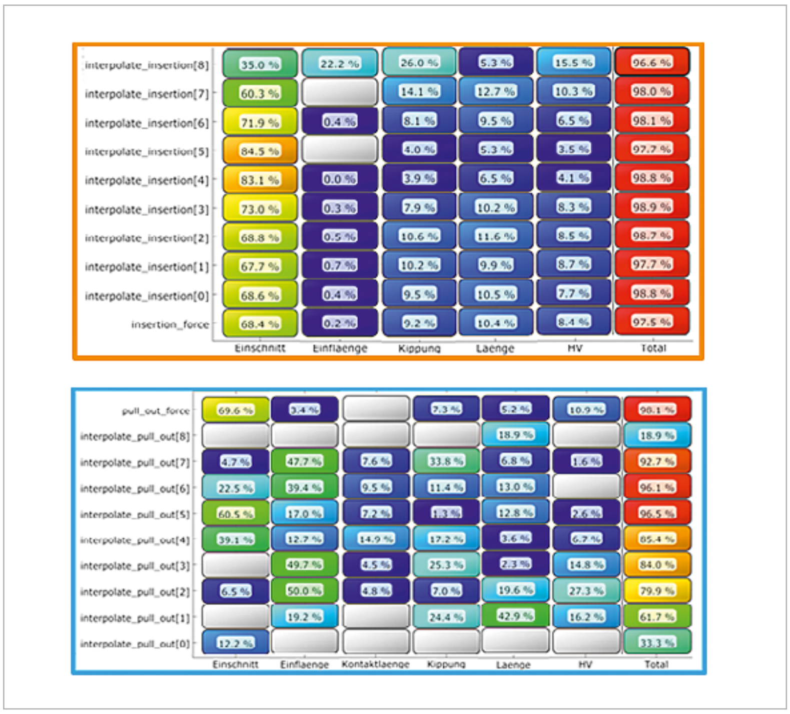

Fig.9: CoP matrix for the interesting marked area of the insertion and pull-out process as a result of the tolerance analysis

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