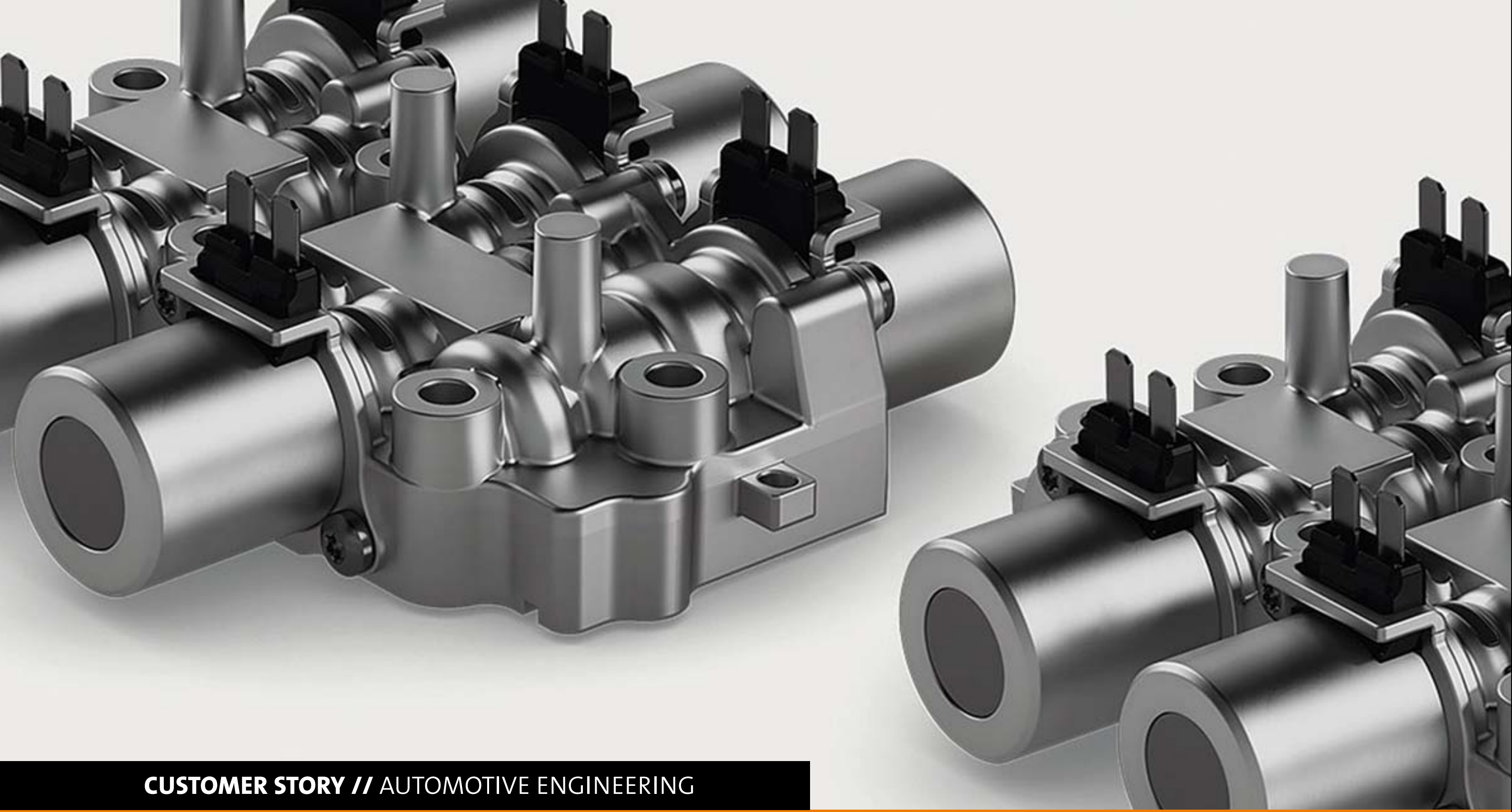

OPTISLANG IN THE FUNCTIONAL DEVELOPMENT OF HYDRAULIC VALVES

optiSLang serves as a link between CFD and system simulations, as well as subsequent optimizations to derive geometric valve designs from customer requirements within the shortest possible time.

Simulation task and general procedure

Functionality of a 4/4-way valve

The product at the center of the optimization is a 4/4-way valve (FINDEISEN), which is used in mechatronics for the automatic gear shifting of a passenger car (see Figure 1). The aim of the hydraulic gearshift is to actuate or operate the gear adjuster via an electrical control signal (current). The gear adjuster is designed with a piston between two chambers. In order to move the piston, oil is pumped into a chamber (PA, PB), whereupon the pressure rises, a force is exerted on the piston and it then moves (gearshift). The opposite chamber must be emptied at the same time (BT, AT) so that no counterforce occurs. The oil flow is controlled via the directional control valve by opening or closing the control edges. By adjusting the flow areas, the flow rate varies according to the orifice equation (MATTHEIS, RENIUS) with

$$Q \sim A(X)\sqrt{dp} \qquad (1)$$

Q is the flow rate, A(X) the open area, dp the pressure difference and X the stroke. Since the area changes over the stroke, the flow rate can be adjusted as a function of the piston position. To adjust the stroke, a proportional solenoid is located on one side of the valve, which generates a force as a function of the current. A spring force acts as a counterforce ensuring an equilibrium of forces between spring and magnet in a defined position, depending on the magnetic force.

Description of the optimization task

Main objective of the investigation is the increase of the flow rate through the valve. In addition to the spring and magnetic forces, flow forces only act on the system during the flow. These forces generate directional disturbances in the dynamic behavior (Q-I characteristic curve) which must be kept as small as possible (FINDEISEN, HUGEL).

The flow forces are only a secondary precondition in this investigation. In common designs these are already optimized, however they must not be neglected, because otherwise already solved problems become visible again, e.g. the peaks in the A-branch move apart.

Figure 2 shows a Q-I curve, where the A-branch (left) realizes the PA or BT flow and the B-branch (right) generates the PB or AT flow. Thus four different flow areas are relevant for the optimization.

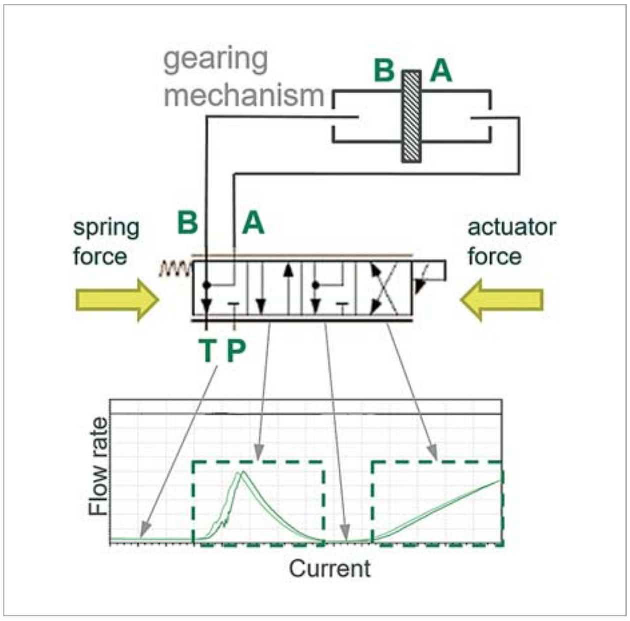

Fig. 1: Switching symbol and explanation of function including volumetric-flow / flow-characteristic curve (Q-I)

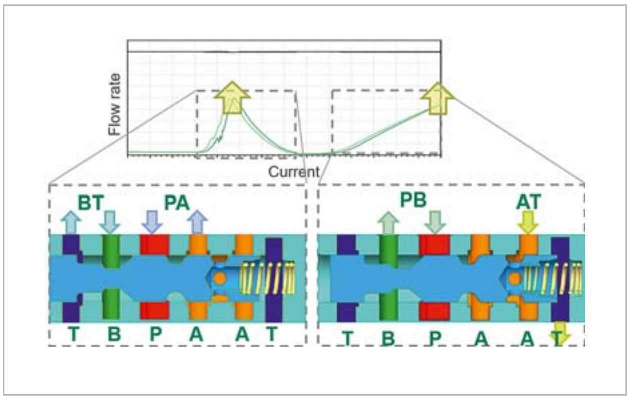

Fig. 2: Q-I characteristic curve with optimization target (yellow arrows) and valve geometry for the PA(BT) and PB(AT) switching positions

Simulation setup and execution

Potential analysis out of the system simulation

Since the optimization task has to be carried out under enormous time pressure, the focus must first be set correctly. In total there are four different port flows, each of which can be influenced by a variation of different geometric parameters. In order to get a feeling for the importance of the individual port flows (flow forces and flow rates) on the Q-I curve, a potential analysis is started. Therefrom the potential of a possible change is to be estimated , in order to carry out a detailed optimization of the geometric parameters only for the relevant control edges.

The system simulation model of the directional control valve is used as the basis for the potential analysis (see Figure 3). The system simulation model generates a Q-I(t) characteristic curve (time-dependent), whereby results from the CFD simulation are used as input. These CFD fields are scaled for the potential analysis.

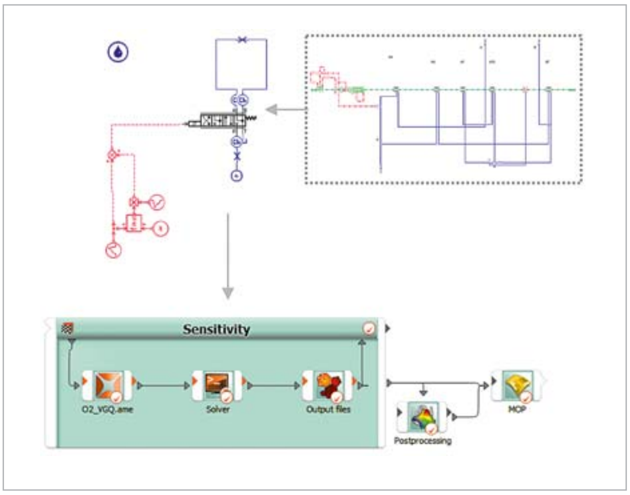

Fig. 3: System simulation model (AMESim, above) and integration into a sensitivity analysis in optiSLang (below)

In the sensitivity analysis, the scalars (and thus the fields) are varied stochastically in order to simulate the Q-I characteristic curve as a function of the field scaling. Although the scaling is not based on an actual geometry fit, it can be used to estimate the potential of each field fit.

Figure 4 shows the Q-I characteristic curve variation (signal plot) based on the field scaling factors and the COP matrix from optiSLang. The variation ranges of the scaling factors are the same, so that their importance can be read directly in the COP matrix.

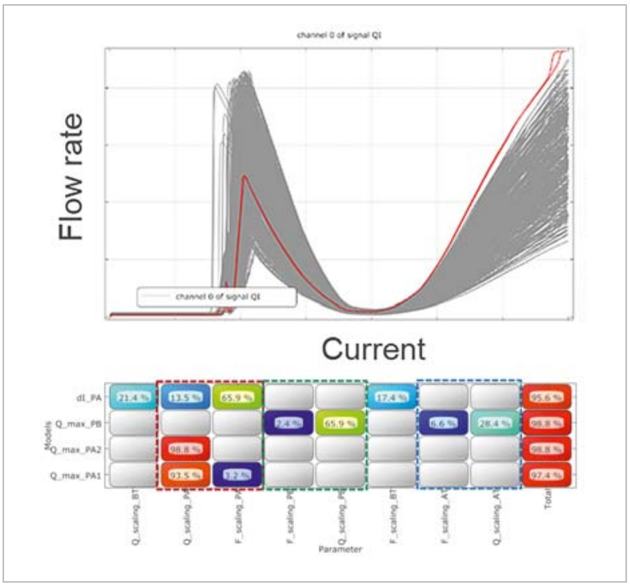

Fig. 4: Q-I characteristic curve variation (top) and COP matrix (bottom) for potential analysis

For the flow rates in the A branch (Q_max_PA1&2), it is shown that the flow rate of the PA flow has the greatest influence (red dotted). For the PB flow (Q_max_PB), the picture is somewhat different. Here both PB and AT must be optimized (green and blue dashed). An important parameter related to the flow forces is the peak offset dI_PA. In

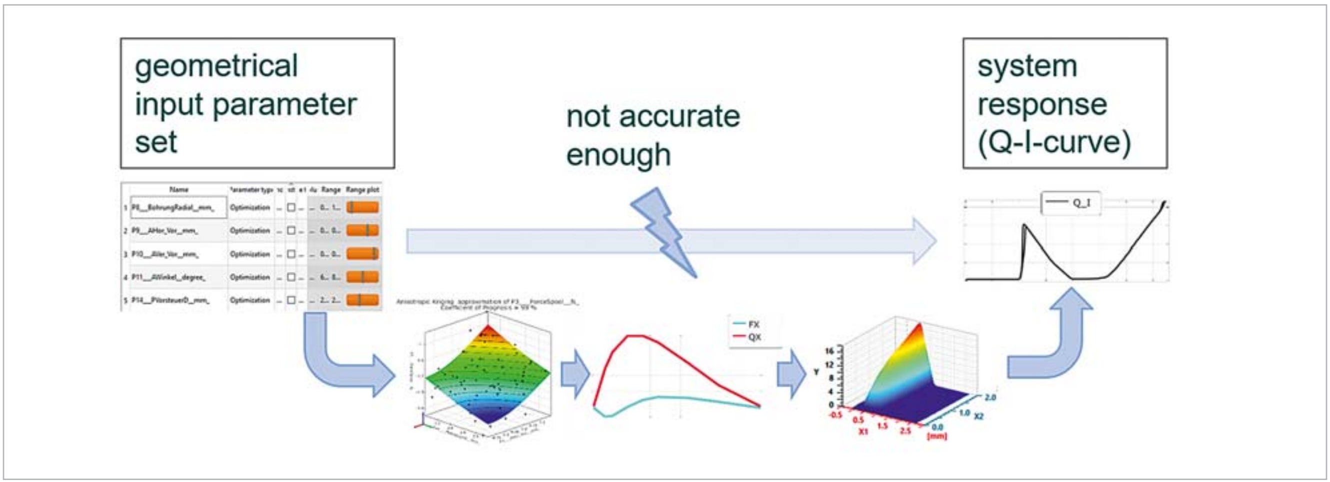

Fig. 5: Procedure for coupling between geometric quantities and system response

this case it can be seen that the flow forces PA and BT have an influence on it. These must always be taken into account in the subsequent optimization process.

Coupling between CFD and system simulation in optiSLang

The potential analysis shows which one of the flow fields has a large influence on the Q-I curve, but it does not show exactly what the geometry looks like that leads to this change.

Figure 5 shows a schematic diagram of the procedure. In principle, it is possible to integrate a variable-stroke opening surface directly into the system simulation with the aid of functions. However, as soon as flow forces play a major role, the models and approximation possibilities are not accurate enough. For this reason, another solution must be found.

This solution lies in the meta-modeling (MOP-solver, MOST, WILL) of the flow force in dependence of geometric parameters. For this purpose, a parametric CFD model (see chapter: MOP creation on the basis of CFD results) must be created in advance. Subsequently, a MOP is generated and integrated into optiSLang (MOP-solver). During the calculation, the MOP is interpolated, whereby a single MOP is available for each stroke position. A characteristic curve (force or flow rate over distance) is then generated and combined into a field using the analytical relationship from equation (1). This field can later be generated for the system simulation using the python script integrated in optiSLang. Since the system simulation is now able to simulate the Q-I characteristic curve, an optimization can be started on this basis for characteristic values, e.g. flow rate at the A port or peak offset.

MOP creation on the basis of CFD results

The heart of the Q-I characteristic curve optimization is the CFD-MOP (HUGEL). Since this is to be interpolated, the COP must be as good (i.e. close to 100%) as possible, which leads to a larger number of design points. At the same time, the CFD simulation should be robust, sufficiently precise and converged. Since all these requirements stand in conflict with the temporally strongly limited task, the workflow must be executed robustly, i.e. for each geometry which can be simulated a proper negative volume (flow rate) must be provided, a grid must be produced with regard to local refinements and a flow calculation must be computed up to convergence (see Figure 6).

The parameter variation (stochastically distributed input parameters, advanced Latin Hyper Cube and the subsequent MOP generation) is controlled by optiSLang and guarantees an optimal ratio between simulation time and quality of the metamodel.

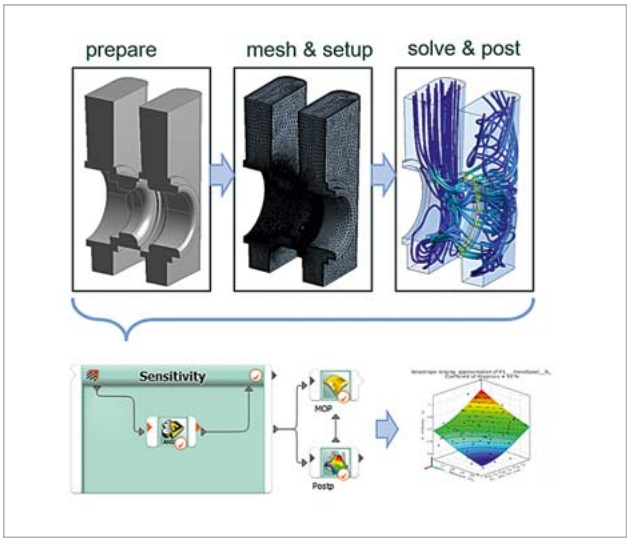

Fig. 6: Integration of ANSYS-Workbench (CFX) in optiSLang for MOP creation for the coupled system

With the help of the COP matrix the suitability of the MOP for interpolation can be investigated. The results show that these are larger than 97% and can therefore be used for further applications.

Optimization system

Since the MOPs of the CFD simulation are sufficiently accurate, the overall system can now be examined. Figure 7 shows the structure in optiSLang. The sensitivity system (left) generates a distribution of the geometric parameters, whereby the forces and flow rates are interpolated using the MOP (based on the CFD results). The data is then bundled in a calculator, processed onwards and forwarded to the python script. At this point the flow fields for the system simulation are created. Afterwards, a standard "AMESim in optiSLang" workflow is started.

Based on the results of the sensitivity analysis, a MOP is generated. Since the COPs are of high quality, the optimization may be started directly on the MOP (much faster). The re-evaluation system generated by optiSLang can subsequently be utilized to run a separate system simulation for the best design.

Various optimizations are started, whereby these only differ according to their criteria. For example, the subcriterion peak misalignment is constrained once barely and once very narrowly.

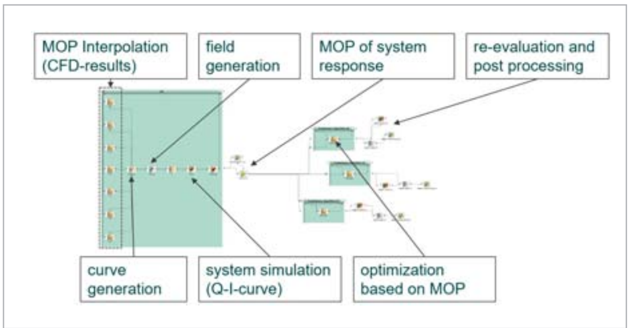

Fig. 7: Coupled Optimization System with subsequent MOP-based Optimization (3 x evolutionary algorithm with different criteria)

Results and re-evaluation

The coupled system delivers several results. First, the COP matrix of the sensitivity analysis is examined more precisely (see Figure 8). The geometric parameters are now displayed in dependency of the system results, which were evaluated on the Q-I characteristic curve. It is noticeable that the COPs are very large, meaning that the MOP is suitable for optimization. The relevant parameters (for the selected variation range) can also be read here (grey dashed).

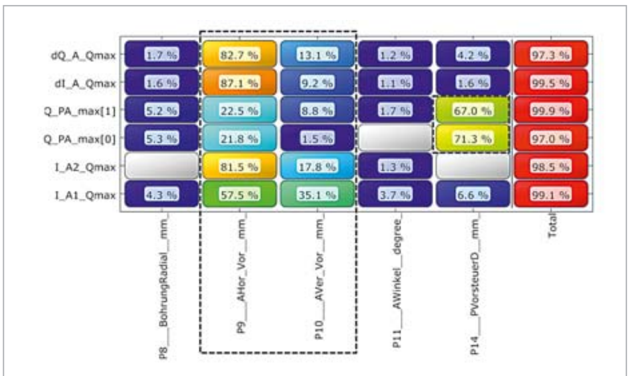

Fig. 8: COP matrix of the coupled system (sensitivity analysis)

Based on this MOP, an optimization by means of an evolutionary algorithm is started. It shows that the external goal to increase the flow rate can be realized without problems. On the basis of this knowledge, the flow rate is only defined as a constraint. The gradient of the characteristic curve and/or the peak offset are used as optimization targets.

The result of a multi-target optimization leads to a Pareto front (see Figure 9), which shows the best designs with regard to the target criteria. The re-evaluated designs, i.e. those recalculated in the system simulation, are shown in green. It becomes apparent that the Pareto front of the MOP optimization is smoother than that of the recalculated designs, but the differences are largely negligible.

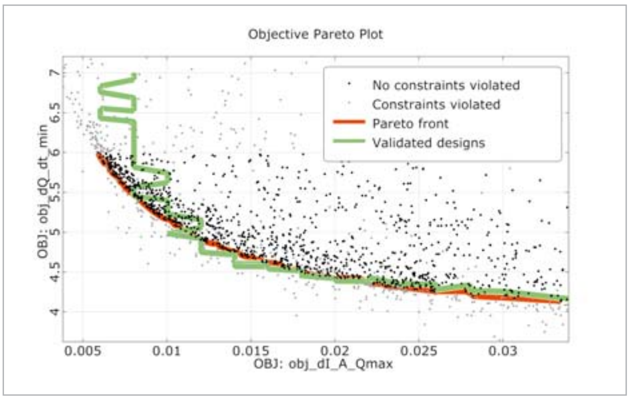

Fig. 9: Pareto front with validated design points

On the basis of the Pareto front, a compromise needs to be found between the two criteria. Therefore, the Q-I-characteristics are considered again. Using this as a basis, a set of parameters containing geometric parameters is derived. Therefrom a concrete design can be obtained.

However, it must be taken into account that the re-evaluated designs were also generated with the help of CFD-MOP. This results in the necessity of a second re-evaluation, i.e. a two-stage re-evaluation.

The process in Figure 6 is repeated with the parameters of the optimized design. Figure 10 (see next page) shows the flow rate and the flow force over the stroke for the MOP interpolated and recalculated variants. The shown convergence of both curves is very satisfactory. The high COP quality of the CFD-MOP can also be seen here.

Finally, the test result of the reference (green) and the target variant (purple) can be compared (see Figure 11). This shows that the gradient in the falling A-branch (optimization criterion) hardly varies, although the flow rate has increased significantly. The flow rates were also significantly increased.

Summary and outlook

When optimizing the 4/4-way valve, various partial ranges for Q-I characteristic curve optimization are possible. In order to analyze which of the ranges have the greatest influence, a potential analysis is performed. This shows the

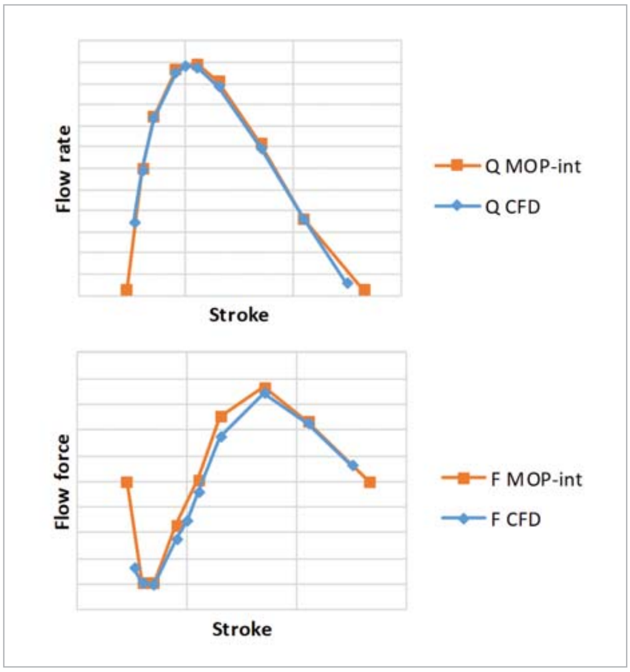

Fig. 10: Volume flow and flow force over the stroke for MOP interpolation and re-evaluated CFD simulation

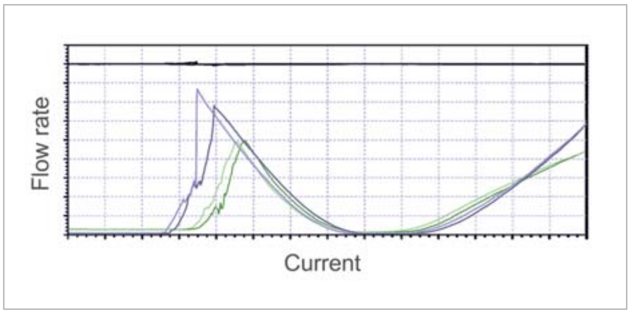

Fig. 11: Measurement results (Q-I characteristic) of the first prototypes (purple) compared to the reference (green)

large influence of the PA, PB and AT flows on the target parameters. By creating a MOP with optiSLang and CFX a correlation between flow forces, flow rates and geometric parameters can be identified. If this MOP is integrated into a coupled system simulation controlled by optiSLang, a relationship between transient behavior (Q-I characteristic) and geometric parameters can be calculated. This is used to calibrate the characteristic to the target functions. Using the workflow shown, a geometry that meets the optimization goals can be found and produced. In addition it offers to the customer the possibility to react quickly to the adaption of the target functions.

The next steps are a robustness analysis using production scatter and, if necessary, an adjustment of the tolerance width of the most important parameters with optiSLang.

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