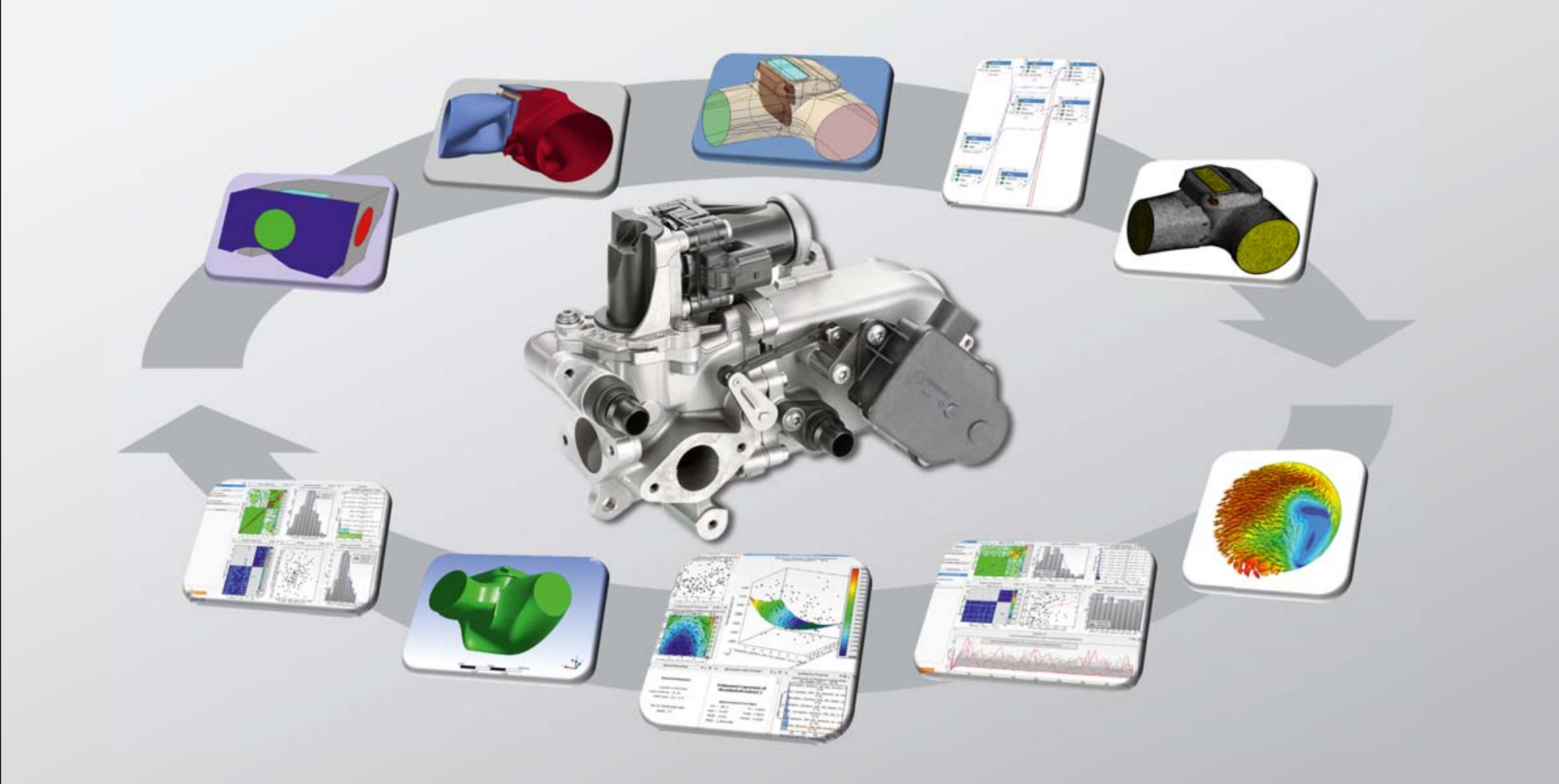

CUSTOMER STORY // AUTOMOTIVE ENGINEERING

NUMERICAL FLUID OPTIMIZATION OF AN EXHAUST GAS FLAP VALVE

From topology optimization results for the valve flow channel, a parametric CAD model is generated for a parameter-based optimization and robustness analysis.

Introduction

In recent years, the reduction of pollutant emissions has become a significant issue for environmental policy, not only because of the latest emission scandals. Consequently, the reduction of pollutant emissions is an eminently important factor in the development of fuel engines. One of the most decisive factors for the reduction of pollutants is the exhaust gas recirculation (EGR). The principle of recirculation ensures that the exhaust gas is partially resupplied to the incoming fresh air, resulting in a reduction of nitrogen oxide emission. Here, an optimized geometry regarding flow-technical aspects essentially ensures a lower pressure loss and a consistent fluid flow.

EGR-process & optimization goal

In this study, optimization objectives for EGR flap valve have been focusing on fluid mechanical characteristics at two load cases for the following reasons:

1. At full load (EGR valve is closed), the lowest possible pressure loss in the entire exhaust gas system is aspired to achieve low fuel consumption of the combustion engine.
2. At partial load (EGR valve is opened; Fig.1), a low-loss inflow into the EGR passage is desired in order to ensure a small scavenging gradient and low throttling to reach the required EGR rate. Additionally, uniform mass flow distribution is required upstream of the EGR cooler in order to ensure high cooling efficiency which is advantageous regarding fuel efficiency of the engine as well.

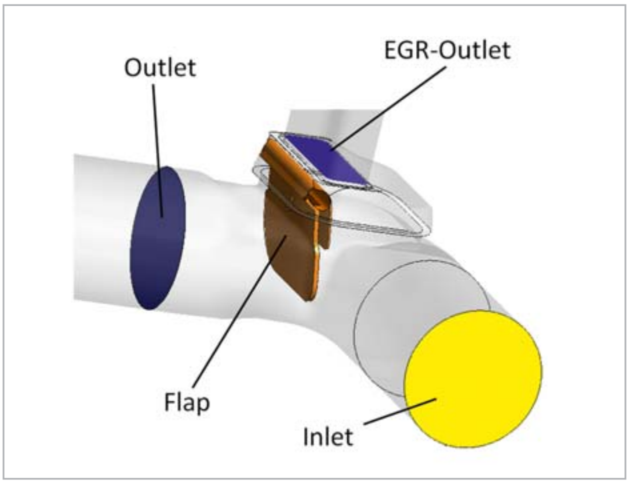

Fig. 1: Flow chamber of an EGR valve

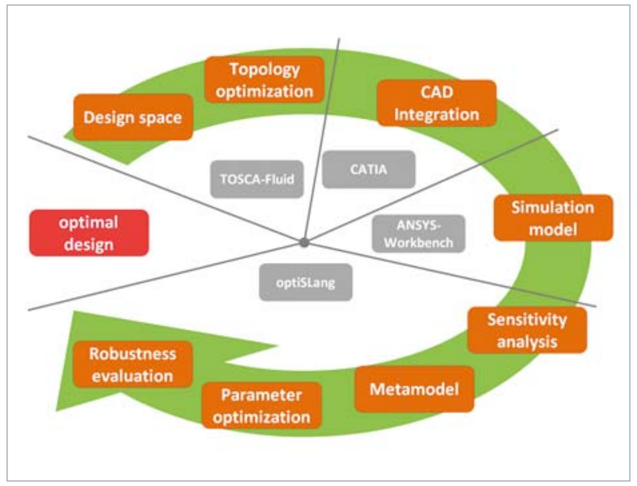

Fig. 2: Optimization workflow

Thus, the objective function includes the reduction of the pressure loss at full load as well as the uniformity of flow towards the EGR cooler in the partial load case.

Frontloading & optimization workflow

The optimization workflow (Fig. 2) is applied at an early project state in order to reduce product development time, to improve technical product quality and to consider maximum innovation potential at the same time. In this context, it is necessary to support the design team already in the offering phase in order to realize active frontloading. For this purpose, a topology optimization of the flow channel is executed for the maximum available design space by the use of Simulia Tosca Fluid. The result is a first conceptual and highly innovative design for both load cases. In the next step, both designs are converted into a parametric Dassault CATIA V5 CAD model which takes manufacturing constraints into account. The implementation of manufacturing constraints and a strong collaboration with the design team during the CAD parameterization ensures meaningful parametric optimization results and reduces the effort in transferring the optimized geometry into the detailed design. By varying the CAD parameters, resulting geometries from topology optimization for both load cases as well as further design states can be represented. The CAE workflow automation and simulation model setup for parametric CAD geometry is defined by the use of ANSYS Workbench. Afterwards, the ANSYS Workbench project is linked to the process steering and optimization software optiSLang. Reasonably, numerical DoE and sensitivity analysis are executed as initial steps in order to explore the entire design space and to build up a database for metamodeling. The sensitivity analysis in particular provides better understanding of complex technical systems and, therefore, adds considerable value to the product know-how. As aforementioned, the resulting database is used to create numerical metamodels which can be referred to optimization algorithms in order to reduce the required amount of CAE solver runs. A minimized optimization objective in combination with a parametric CAD model yields to a design which covers improved flow characteristics for both load cases. Finally, robustness evaluations of the optimized design are executed with regard to scattering measures in the manufacturing process or in the operating conditions.

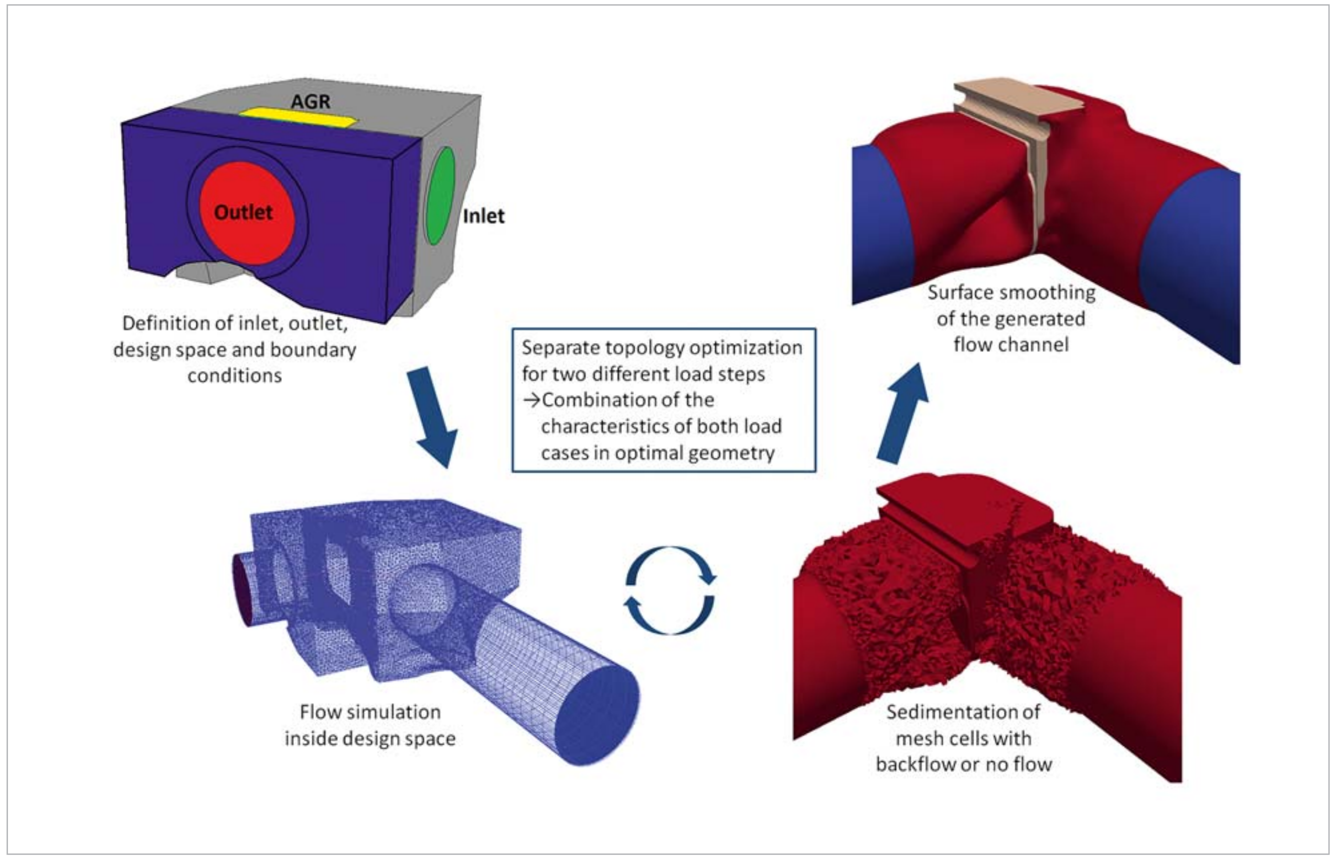

Fig. 3: Principle of topology optimization

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Topology optimization

Topology optimization is a non-parametric approach (Fig. 3). In this study, the software Simulia Tosca FLUID simulates the sand deposit behavior of rivers to detect an optimal flow channel design for the available design space. Thus, it is a bionic approach which is able to result in very innovative design concepts. This is furthermore promising in the context of application of modern manufacturing processes (i.e. ALM).

This approach is typically used in tasks dealing with pressure loss reduction, flow homogenization and mass flow balancing. Since only an available design space and load case is required for this optimization type, it can be used perfectly for frontloading activities.

Boundary conditions & design space

First, the boundary conditions for the fluid mechanical simulation are defined corresponding to the load case of interest. In the following step, locations of the fluid inlet and outlet as well as the boundaries of the design space are determined. The flap operation area is defined as non-design space. Thus, it is not possible to apply a topology optimization algorithm for the sedimentation.

Meshing & simulation setup

The CAD design space is defined with Dassault CATIA V5 and meshed with ANSYS ICEM CFD. Afterwards, the resulting mesh is imported into ANSYS Fluent in order to define the CFD simulation model setup used by Simulia Tosca Fluid. Performing a test is recommended in order to check whether the simulation setup is suitable for a topology optimization run. The topology optimization is carried out separately for each of the two load cases with corresponding boundary conditions:

- LC1: full load, flap closed
- LC2: partial load, flap opened

Optimization & sedimentation

During the optimization run with Simulia TOSCA Fluid, a connected ANSYS Fluent simulation is performed in the background. Additional variables represent the sedimentation behavior. TOSCA Fluid iteratively evaluates those variables for each mesh cell in the design space of the current iteration. It deactivates or sediments cells with regard to occurring backflow or no flow. Hence accessible design space is iteratively modified for Simulia TOSCA Fluid. Finally, the topology optimization algorithm converges to a flow channel contour which provides "positive" flow for all mesh elements. All sedimented elements are eliminated in the resulting geometry file.

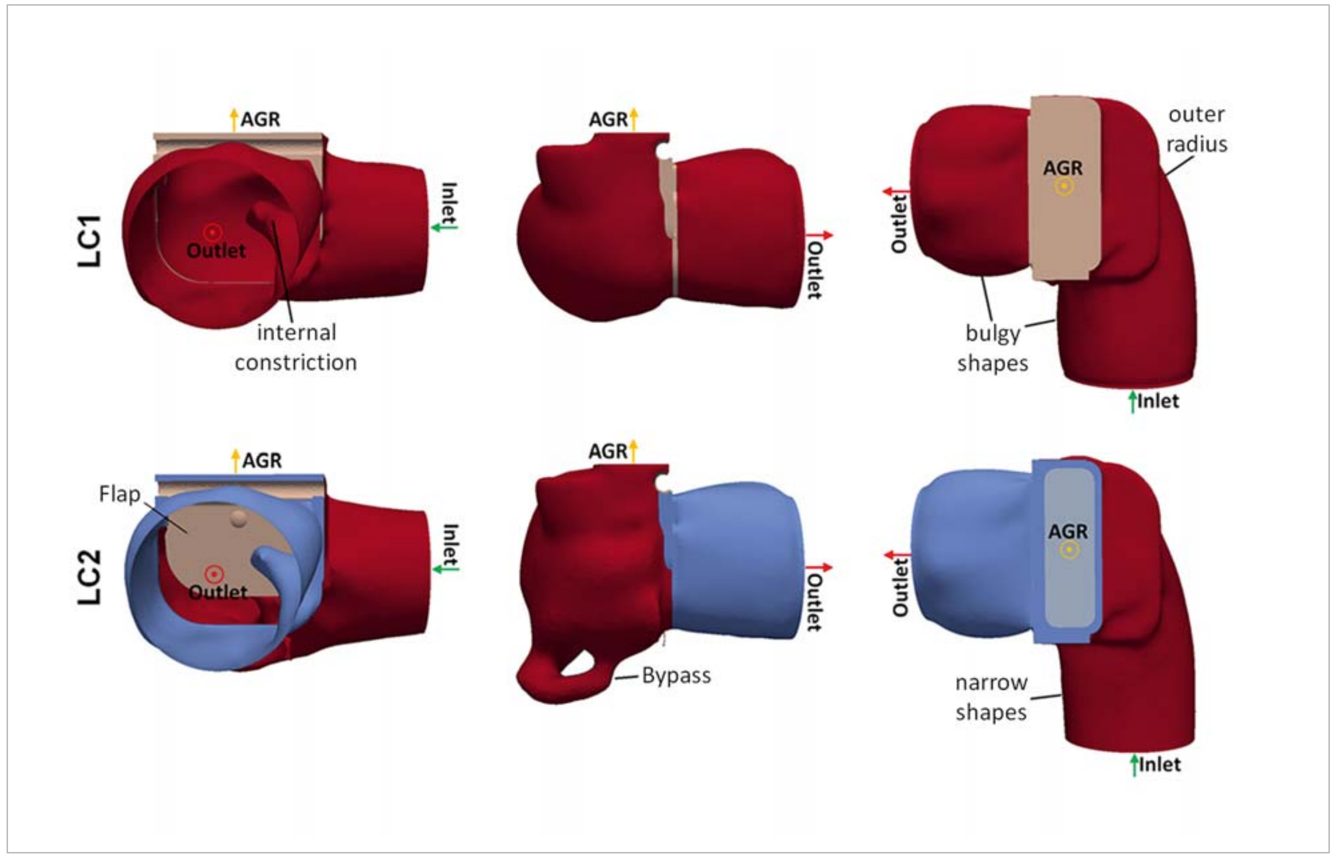

Fig. 4: Results of the topology optimization

Smoothing & significant features

The final step in topology optimization is the smoothing process. Since the result of the raw topology optimization shows tessellated surfaces representing the unsedimented cells of the design space (i.e. flow channel contour), it cannot be used for the further CFD process. A simulation run validating the results of the topology optimization is required due to assumptions related to optimization principles (i.e. resolution of near wall flow is insufficient during topology optimization). Thus, the unsedimented mesh elements are smoothed with regard to the flow direction in order to provide a homogeneous flow channel contour. Depending on the optimization task, smoothing results may be not satisfying. Consequently, a geometry return after the topology optimization has to be performed with the CAD software. From the smoothed results of the topology optimization of the EGR flap valve, significant characteristics can be derived for both load cases.

As shown in Fig.4, increasing cross-sectional areas downstream of the inlet and upstream of the outlet resulting in bulgy shapes are noticeable. In addition, there is a continuous curvature targeting towards the outlet without considering the maximum dimension of the flap operating area. In contrast to LC1, a continuous curvature is modified in LC2 in order to provide a perpendicular flow towards the EGR cooler outlet. The bypass channel supports this effect by conducting the flow parallel to the flap position towards the EGR cooler outlet. The inner constriction (blue face in Fig. 4) is a significant characteristic at the outlet but cannot be manufactured because of demolding restrictions.

CAD-implementation

At first, only the flow channel is modeled and parameterized by the design department. Afterwards, the flap with its associated connection to the EGR cooler as well as the draft angles are added to the CAD model. Spline curves are used to represent the complex surface of the flow channel contour resulting from topology optimization runs. For this purpose, the smoothed resulting geometries from Simulia TOSCA Fluid are visualized using a line curve model, which is derived from cut planes located orthogonal to the main flow direction in specified intervals.

In order to create a parameterized CAD flow channel, which is capable of accurately representing the results from the topology optimization, a total of four supporting cross-sections are defined (Fig. 5): the inlet (IN), the outlet (OUT), the flap seat (THR) and the intermediate position between inlet and flap (ZW). The last one is variable parallel to the flow line. The four cross-sections are connected via spline curves with an offset of 90° (along circumference) at four support points (1, 2, 3 and 4). The curve stiffness and curve starting angle can be modified at each supporting point for each spline curve. The stiffness is a measure which determines the influence of the angle at a certain distance from the supporting point along the spline curve. Finally, the support cross-sections and spline curves are used to model a closed volume for the EGR flow channel. This procedure results in a total of 56 input parameters.

Afterwards, the geometry of the flap is added to the component including the connection to the EGR cooler (Fig. 6). Furthermore, geometric manufacturing restrictions are implemented. During the parametric optimization, both load cases use identical flow channel contours, but the flap position differs. Thus, two models are created: one with closed flap for LC1 and one with open flap for LC2. The two resulting geometries from the topology optimization can now be represented via a certain input parameter set for each load case.

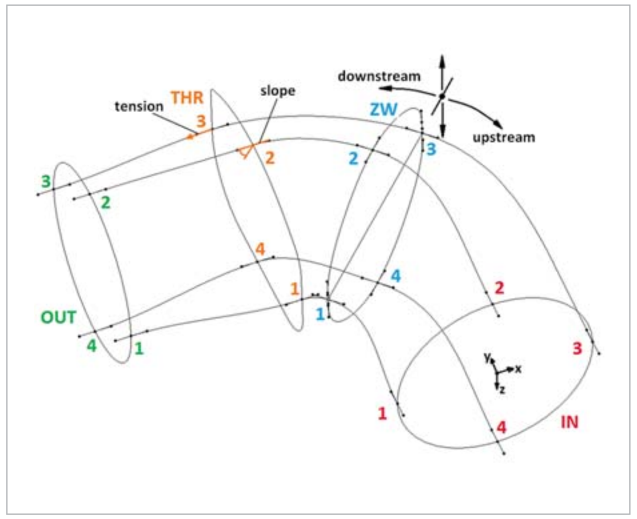

Fig. 5: Generation of a CAD-geometry

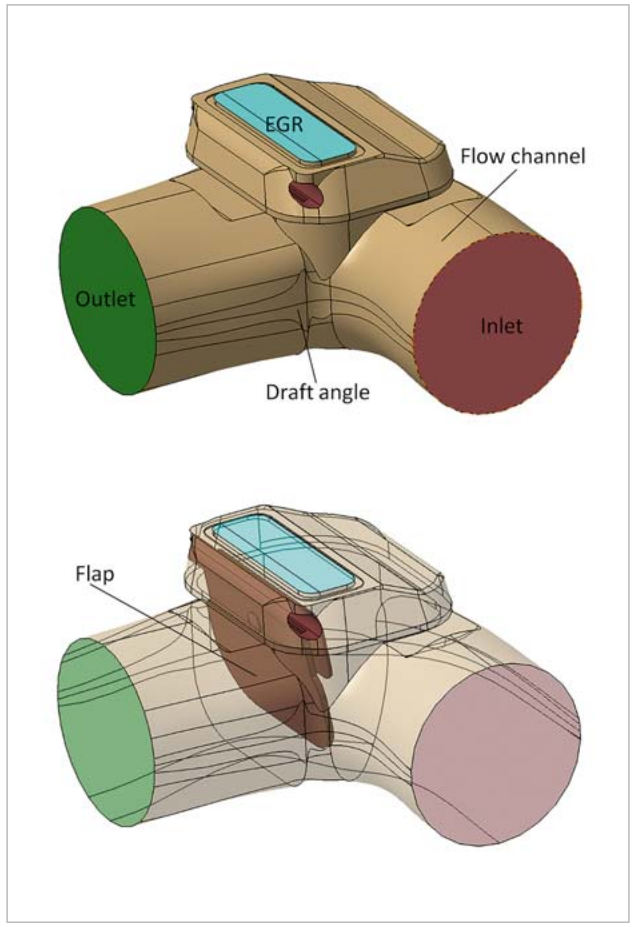

Fig. 6: Parametric CAD-Model

Sensitivity analysis

A numerical Design of Experiment (DoE) is performed using state-of-the-art space-filling sampling plans like Latin Hypercube Sampling (LHS). Due to its independence from the number of input variables, a maximum of approximately 120 solver runs is required to provide a useful database for metamodeling. The input parameters (CAD, operating conditions etc.) are varied based on the DoE plan and output parameters (systems responses which are part of the objective function and constraints) are determined. The DoE results are investigated in a sensitivity analysis to identify important parameters as well as correlations and non-correlations. The resulting metamodel is a n-dimensional mathematical description of the most important correlations and interdependencies and can be used by optimization algorithms or, for example, as a pre-dimensioning tool.

Design of Experiments (DoE) & metamodel

In this study, 148 designs (including failed designs) are generated using the method of Advanced Latin Hypercube Sampling. Due to the complexity of the geometry model, the dependencies, correlations and sensitivities of the parameters are difficult to describe. A gradual reduction of parameter limits and the identification of superimposed parameter functions result in a re-examined 31 of the total of 56 geometry parameters of the EGR valve. This increases the prognosis quality of the response variables with regard to the input parameters. The required magnitude of 80 percent of the prognosis coefficients is thereby nearly fulfilled for the most important outputs.

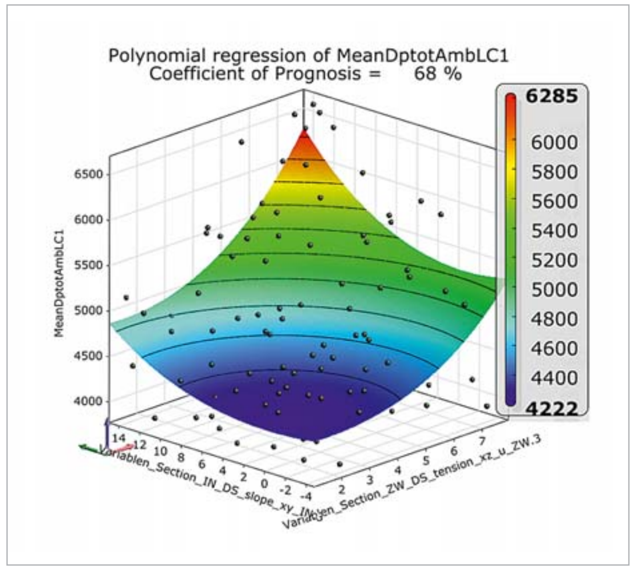

Fig. 7: Metamodel for the objective function value

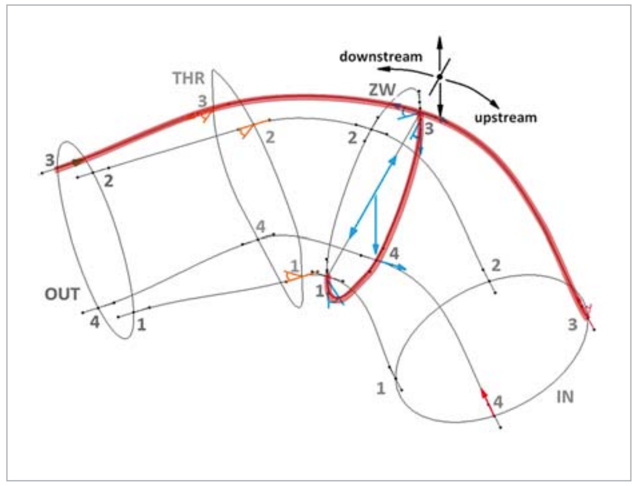

Fig. 8: Sensitive parameters on the outer surface and the lower support cross-section

The result of the sensitivity analysis is a metamodel with a total of 15 sensitive parameters with respect to the objective function and constraints (Fig. 7). The main influence is on the outer contour and the lower support cross-section of the CAD model. The arrows in Fig. 8 symbolize the tension parameters, while the angles represent the slope parameters.

Parameter optimization

Optimization algorithms are used to vary the input parameters of the parameterized model. They minimize the objective function under the consideration of constraints. Single or multiple objective optimizations could be performed. To have a sufficient starting point for the optimization run, it is recommended to use the best design of the DoE as start design. If a metamodel with high prognosis quality is available, it is used in the pre-optimization. The Pre-optimization uses algorithms, such as Evolutionary Algorithms (EA) which are not limited to a number of input parameters but require a lot of iterations. Since a metamodel is used to determine the system response and no additional solver runs are required, more than 1000 iterations are not critical. Thus, pre-optimization is a “cheap” method which helps to identify a sensitive subspace for the final optimization. This optimization is conducted to find the global optimum in the design space. For this task, particular algorithms are used, such as adaptive response surface methods (ARSM). However, they cause limitations, i.e. max. 15 input parameters. In addition, the final optimization is “expensive” since it performs solver runs in each optimization iteration.

The objective function for optimization is defined on the basis of the output parameters which are minimized regarding the constraints. The minimization of the total pressure loss in LC1 is the most important objective valued with a rating of 60 percent. The equal distribution of the flow towards the EGR cooler is weighted at 30 percent and the static pressure loss in LC2 in the direction of the cooler at 10 percent. In order to achieve the EGR rate, it is important to develop a coun-

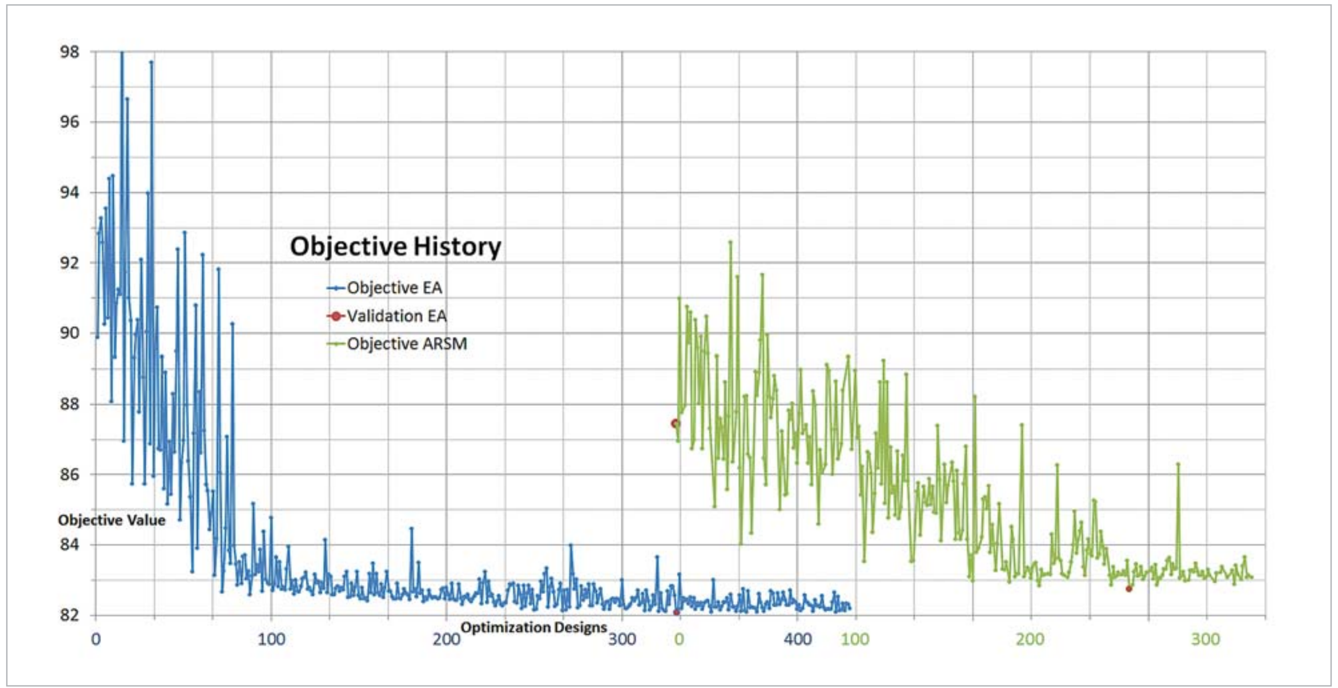

Fig. 9: Course of optimization

ter pressure in the direction of the exhaust pipe in LC2. This is defined in a constraint with a minimum value for the static pressure loss. Furthermore, the resulting forces on the flap must not be larger than in the reference model.

Global pre-optimization

The pre-optimization on the metamodel is performed using the entire data set of the sensitivity analysis. The best designs of the sensitivity analysis, regarding the objective function and constraints, are used as a starting population for the optimization using an evolutionary algorithm. Due to the prognosis values lower than 80 percent from the sensitivity analysis, it is difficult to find an optimal design, which can be confirmed by the validation computation. After several runs of generating predictable metamodels, a design was determined indicating the lowest value in the objective function. Nevertheless, it deviates from the value of the metamodel prognosis.

Final optimization

For the final optimization, the parameter set is reduced to the 15 most sensitive parameters derived from the sensitivity analysis. The best design of the pre-optimization is used as a start design. The result of the optimization is a further improvement compared to the validated solution of the pre-optimization. The inaccurate prognosis of the optimization on a metamodel can nearly be achieved regarding the result value (Fig. 9).

Result of the parameter optimization

In comparison to the optimal geometry from the topology optimization, some significant similarities and differences occur in the shape of the flow channel (Fig. 10). The evolution of the

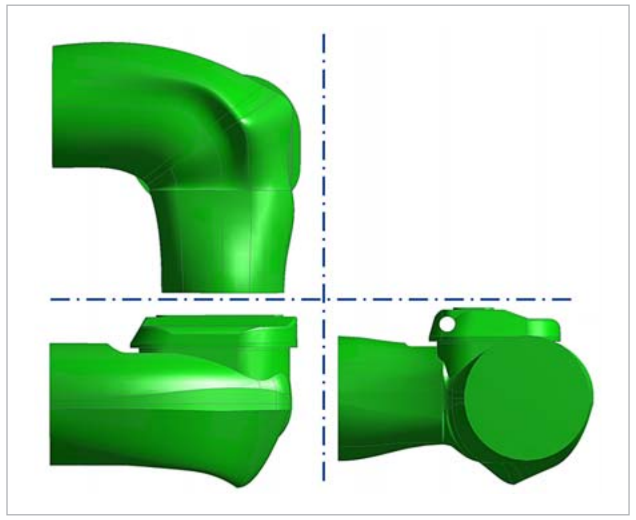

Fig. 10: Result of the parameter optimization

bypass is very noticeable in the geometry derived from the parameter optimization. However, compared to the topology optimization, the same extent of shape development cannot be observed. The inner restriction does not occur as a result of the parameter optimization. As another characteristic outcome of the topology optimization, the bulgy shape at the inlet as well as the outlet to LC1 does not appear as a result of the parameter optimization. The tendency is rather towards the narrow connection at the inlet, which is the result of the topology optimization in LC2.

Robustness evaluation

A robust design is defined as a part which is less sensitive towards inevitable scattering of input parameters (material, geometry, load cases etc.). Thus, the variability of the

product behavior is reduced. This in return leads to an improved predictability and has a positive influence on the assessment of risk. By applying uncertainties and scattering in terms of statistical measures on the optimized design, the robustness can be evaluated (sigma level). In this study, the scattering of possible influencing factors on the flow of the exhaust gases in the valve is considered, e.g. the temperature of the exhaust gas, the mass flow, the pressure of the flow, the flap angle, the accuracy of the flap and the production tolerances of the components.

As a result of the robustness evaluation, a very dominant influence of the ambient pressure and temperature can be observed. The scattering of the production conditions causes only minimal influences. This is an important conclusion for the tolerance management in the manufacturing process. Furthermore, it can be seen that the inaccuracy of the angular adjustment has no influence on the scatter of the result values. This is also useful information for the setting of the motor operating points.

Conclusion

Fig. 11 and 12 show the changes in geometry and its flow characteristics after each optimization step. Here, the evolution of the geometry shape can be seen. The external shape of the geometry especially changes, since the responsible sensitive parameters were determined. The locally occurring maximum pressure on the flow channel wall decreases as a result of the optimization. In addition, the pressure difference between the inlet and the outlet has dropped, which can be seen in the color scale. This is due to the changed geometry for the redirection of the flow. This feature represents a contrast compared to the topology optimization where the outer radius has a harmonically rounded shape around the flap operating area.

Fig. 11 shows the process of how the EGR valve could be optimized in comparison with the reference geometry. The continuous improvement indicates the benefit of each optimization step. In Fig. 12, the result values regarding the objective function variables are compared. The value of the objective function has decreased by 38 percent. The total pressure loss for LC1, as the most important variable, could even be reduced by almost 45 percent.

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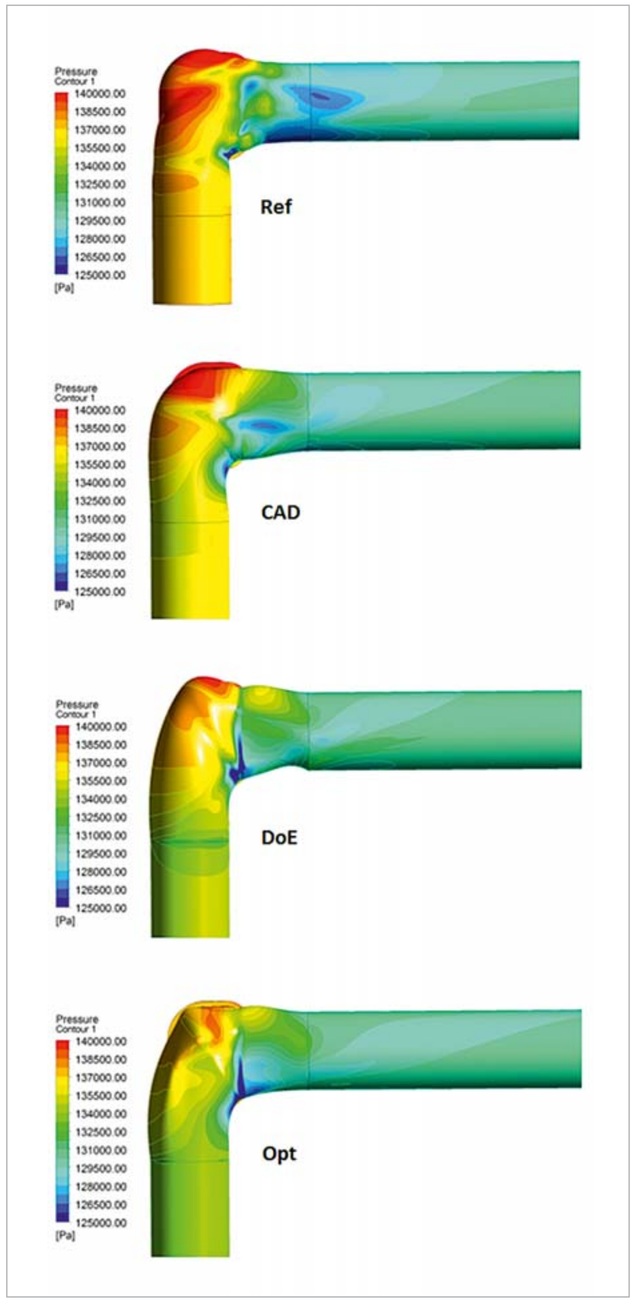

Fig. 11: Course of optimization – static distribution of pressure

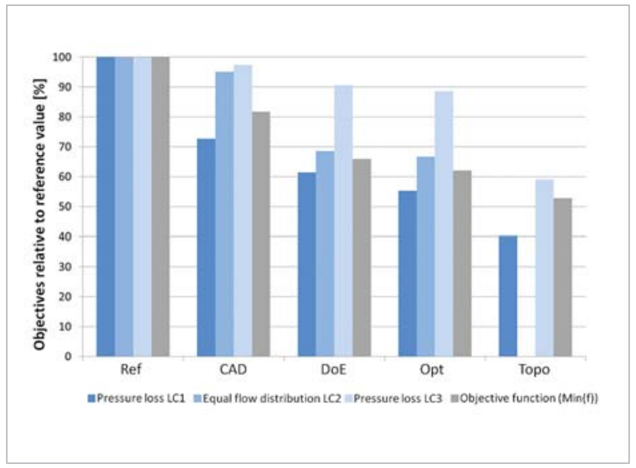

Fig. 12: Course of optimization – values of the objective function