Aerodynamic Design Optimization of a Dual Element Rear Wing

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Summary:

A dual element rear wing of a race car was aerodynamically analyzed and optimized by modifying the position and the angles of the wing elements. Both the steady-state RANS simulation as well as the optimization were performed in STAR-CCM+, whereas the CAD geometry was retained and modified in NX. In each design iteration, NX received the parameters proposed by the optimizer in STAR-CCM+, modified the geometry and sent it back to STAR-CCM+ via a bi-directional interface. The updated geometry was then automatically re-meshed and the RANS simulation for the design was run in STAR-CCM+. The optimization resulted in a significant improvement with respect to downforce and drag compared to the initial configuration.

Keywords:

Simcenter STAR-CCM+, Siemens NX, STAR-NX, HEEDS, SHERPA, CAD interface, Design Study, Design Optimization, Aerodynamics

1 Introduction

In this paper, a geometric design optimization study of the rear wing of a race car is described. The rear wing delivers downforce, which is required to increase the maximum cornering speed, but it also produces drag, which limits acceleration and straight-line speed. The two wing elements are connected by end plates on both sides. The geometry is shown in Figure 1. The horizontal and vertical positions along the end plates can be considered as design parameters. The pitch angles of the wings are adjustable. The design goal was to find a configuration which produces high downforce, but relatively small drag force at a given velocity. Therefore, the parameters to be considered are the vertical and horizontal positions as well as the pitch angles of both wings.

The geometry was created and modified in Siemens NX. The CFD simulations were performed in Simcenter STAR-CCM+. The design optimization cycle was controlled by Design Manager, a tool for parameter studies and optimization which is included in STAR-CCM+. During the optimization, the design parameters were sent from STAR-CCM+ to NX and the modified geometries were transferred back via the CAD client *STAR-NX*, which is a plugin for NX and provides an interface for bi-directional communication.

Section 2 of this paper describes the workflow for the design optimization study. Section 3 outlines the numerical modelling. Section 4 describes different approaches for design optimization. The results are shown in section 5, and some conclusions are drawn in section 6.

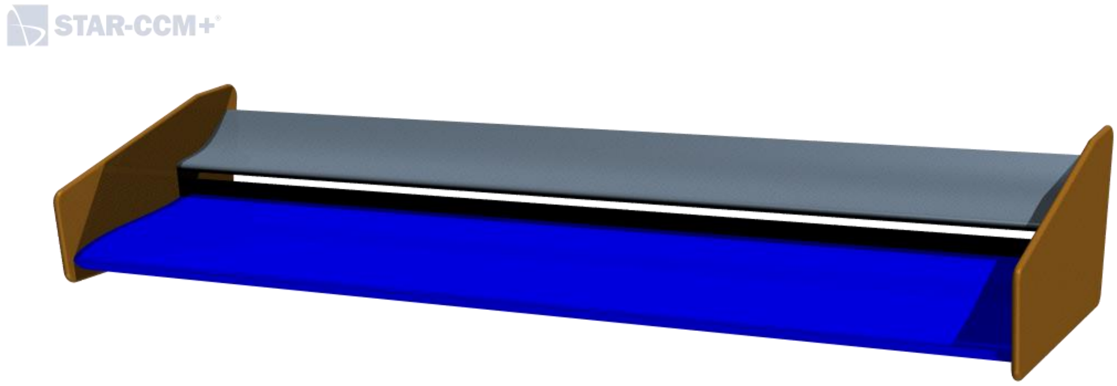

Figure 1: Geometry of the dual element wing (blue: large wing, grey: small wing, brown: end plates)

2 The workflow

1) The initial configuration is created as a parametrized geometry in **Siemens NX**
2) The geometry is transferred to Simcenter STAR-CCM+ using the NX plugin **STAR-NX**, which enables direct communication between NX and STAR-CCM+ and exchange of geometries directly over the memory, without file I/O
3) The numerical setup and the computational mesh are created in **Simcenter STAR-CCM+**
4) Optimization studies are performed with **Design Manager**, a dedicated tool for parameter studies and optimization within STAR-CCM+, which controls the following optimization cycle:
    a. **Design Manager** sends the design parameters to STAR-CCM+
    b. **STAR-CCM+** requests an updated geometry from NX via the interface STAR-NX
    c. **NX** modifies the geometry according to these parameters and sends it back to STAR-CCM+ via STAR-NX
    d. **STAR-CCM+** meshes the modified geometry and runs the simulation
    e. **Design Manager** obtains the results (response functions) for the design from STAR-CCM+, decides on new parameter values based on the previous and the current results, and the cycle starts again
5) Post-processing of the results is done using **Design Manager** as well as **HEEDS Post**

The workflow is illustrated graphically in Figure 2.

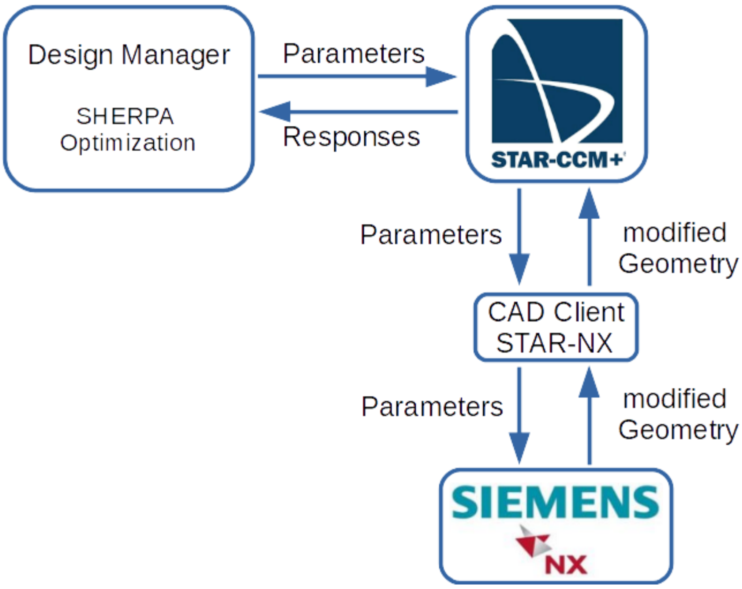

Figure 2: The workflow for design optimization with NX, STAR-CCM+ and Design Manager

3 Numerical Modelling

3.1 Geometry

The rear wing is a dual wing configuration with end plates on both sides. Only half of the geometry is modelled and a symmetry boundary condition is applied in the simulation in order to reduce the computational workload. The full geometry is shown in Figure 1. It was created in Siemens NX using a feature-based workflow with all important geometric dimensions defined as expressions. The relevant expressions are then made available as simulation parameters to STAR-CCM+ and Design Manager.
The wings are undisclosed cambered airfoils with thicknesses of 18 % and 12 % for the large and the small wing, respectively. The chord lengths are 0.3 m and 0.15 m. The length of both wings is 1.4 m, or 0.7 m for the symmetric half geometry. The wings are connected and bounded by an end plate of length approx. 0.4 m, height between 0.14 and 0.23 m. In the initial configuration, the noses of the large and the small wing sit at 16 and 267 mm, respectively, behind the leading edge of the end plate.
The geometry was transferred to Simcenter STAR-CCM+ using the plugin STAR-NX, which enables direct communication between the CAD kernel of NX and the STAR-CCM+ server process.

3.2 The computational mesh

The unstructured computational mesh was created in STAR-CCM+. Polyhedral cells were used in the volume except for the near-wall regions, where prismatic layers with a geometric thickness distribution were used in order to resolve the turbulent boundary layer.
The (symmetric) computational domain surrounds the dual wing in the shape of a half-sphere with radius 8.0 m, which is approximately 27 times the chord length of the larger wing or 20 times the length of the total geometry.
The large and the small wing are resolved with around 50 and 30 polygonal cells along chord, and around 90 cells in the spanwise direction of the half wing (except for the nose, where the cells are smaller in order to resolve the curvature of the geometry). Several areas of mesh refinement were placed in the vicinity and in the wake of the wings.

3.3 Physics modelling and boundary conditions

For each design, a steady-state RANS simulation was run. The flow was assumed to be fully turbulent, and turbulence was modelled with Menter's k-Omega-SST model [1]. The air is assumed as an ideal gas. Wall boundary layers are well resolved by the mesh in most places, but a wall function approach was used in order to appropriately treat the areas with relatively coarse wall-normal resolution.
Each simulation started from a homogeneous field regarding longitudinal velocity and a constant pressure field as the initial conditions. Convergence was monitored based on the residuals as well as on downforce and drag force as integral metrics, and the simulations were run until a reasonable level of convergence had been reached.
At the outer boundaries, a free stream condition was applied with a flow speed of 200 km/h, pressure of 1013.25 mbar and a temperature of 26.85 °C (300 K). The walls are no-slip (viscous) walls.

3.4 Numerical methods

The Navier-Stokes equations are solved in STAR-CCM+ using a Finite Volume Method by the Segregated Solver, which is a pressure-based solver using the SIMPLE algorithm for pressure-velocity coupling (cf. e.g. [2]). Energy equation is not solved as the air is assumed to be isothermal. All convective and diffusive fluxes are approximated by the default second-order upwind schemes [3].

4 Design Optimization

Design optimization was done within STAR-CCM+ using Design Manager. This tool uses the optimization algorithm SHERPA, which is a combination of local and global, gradient-based and stochastic schemes and has shown very good performance for a variety of engineering problems [4].
The parameters used in the optimization were the

- vertical position
- horizontal position, and
- pitch angle,

each for the large and the small wing, i.e. six parameters in total. The values of the parameters are bounded by geometric constraints, e.g. the wings have to stay well within the end plates and the positions should be chosen such that they do not collide for a range of pitch angles. The limits to the parameter values are shown in Table 1. Each value is an offset with respect to the initial configuration. In order to obtain simple values for the parameters, increments of 2 mm and 1 degree were allowed for the lengths and the angles, respectively.

Parameter	Minimum	Maximum
Large wing horizontal position [mm]	-16	4
Large wing vertical position [mm]	0	20
Small wing horizontal position [mm]	0	20
Small wing vertical position [mm]	-18	2
Large wing pitch angle [deg]	-5	12
Small wing pitch angle [deg]	-15	20

Table 1: The design parameters with their minimum and maximum values

The objectives to be optimized in the design study were

- downforce, and
- drag force

for the entire (half) dual wing configuration.

The downforce and the drag force are both computed from the local surface forces, where the downforce is defined in the vertical direction and the drag force in the horizontal direction with respect to the motion of the wing.
For evaluation, the ratio of downforce to drag force is used as an additional metric. This quantity will be called D/D ratio in the following (i.e. downforce-to-drag ratio).

As the optimization has two conflicting objectives, there are multiple ways to assess the performance of the design. In this study, the following approaches are used:

- *Resolution of a Pareto front*: a point on the Pareto front is optimal in the sense that there is no other point in the design space which is at least equally good in one objective and better in the other. This does not provide a single optimum, but a whole curve of formally equally feasible designs. The preferred design can then be chosen either graphically or by the introduction of weights for the single objectives, and is basically an engineering decision
- The *D/D ratio* as scalar response function
- A *weighted sum of the objectives* as a scalar response function

For each of the approaches, a separate design study was run with 100 designs each.

5 Results

5.1 Pareto front

This approach resolves the Pareto front without deciding for weights on the single objectives, i.e. without specifying any preference for one or the other objective. Design Manager provides the optimization type *Multiple Objective Tradeoff (Pareto)* in order to do this. The results are shown as green crosses in Figure 3. This method creates a very broad range of designs and gives a good overview over the design space. It is therefore well suited to get an overview over the design space. However, it also creates designs in regions of the design space which we are not interested in. For instance, the designs in the bottom left of Figure 3 show both very low downforce and very low drag, whereas the designs at the top right provide very high downforce, but at an unacceptably high drag. In contrast, relatively few points are located in the area between downforce 600…900 N. Another study is required if a better resolution of this area is needed.

5.2 D/D ratio as scalar response function

This next approach combines the two conflicting objectives into one single objective by using the ratio of downforce and drag. For this single objective, a maximum is sought (i.e. downforce should be large compared to drag).

Figure 3 shows the results in red solid circles. It is obvious that optimizing for maximum D/D ratio in this case leads to designs which tend to produce small downforce as well as small drag, which is not our overall design target. This makes this approach less feasible in this context. The best design in this sense is listed in Table 2.

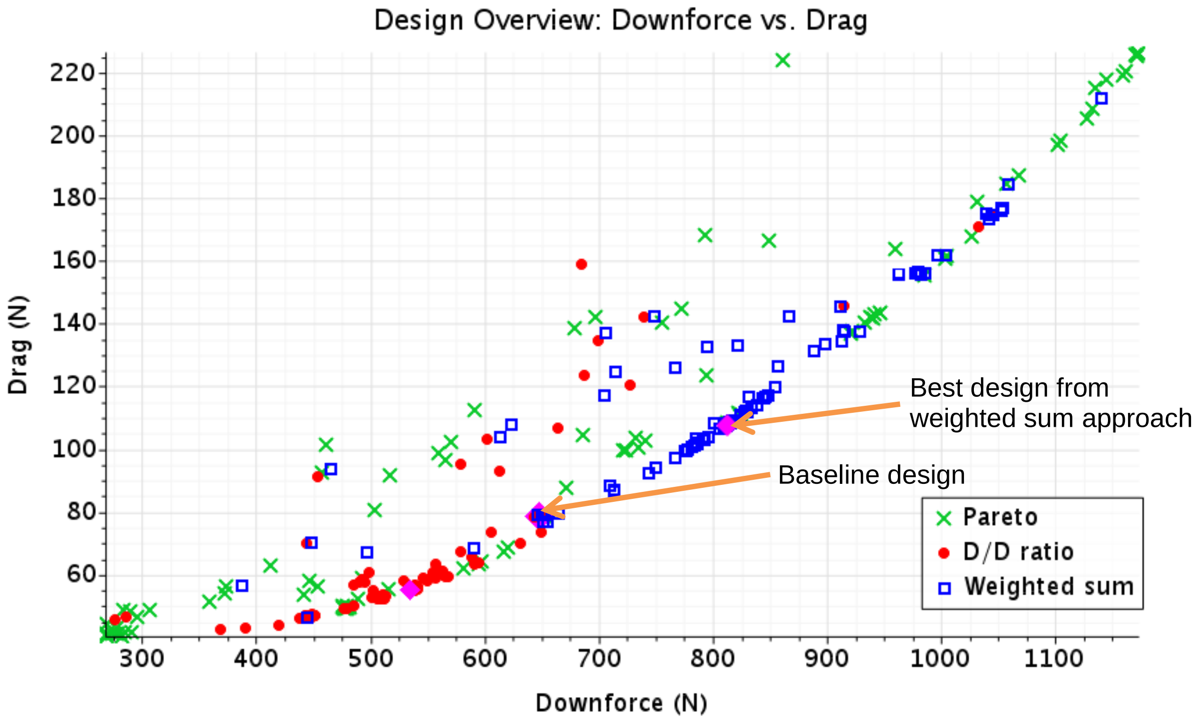

Figure 3: Results from the optimization studies, Drag force vs. Downforce

5.3 Weighted sum of the objectives

In order to obtain high resolution in the central part of the Pareto front, where moderate downforce and moderate drag are found, a performance function is chosen based on a weighted sum of downforce and drag. As large downforce is more important than small drag, the downforce is weighted with a factor of 2 and the drag with -1 (the negative sign is required as we want to achieve small drag). This leads to the performance function (to be maximized):

$$P = 2\,L - D$$

This yields the results which are shown with blue hollow squares in Figure 3. We see that the optimizer chooses most designs in the center of the diagram, while even resolving the Pareto front quite well in this area. The best design according to this performance function is listed in Table 2 and marked by an arrow in Figure 3. With respect to the performance function, this design is 25.3 % better than the baseline design, which is also marked in Figure 3.

Design	Down-force [N]	Drag [N]	D/D ratio	Weighted sum [N]	Hor. pos. large wing [mm]	Vert. pos. large wing [mm]	Hor. pos. small wing [mm]	Vert. pos. small wing [mm]	Pitch large wing [deg]	Pitch small wing [deg]
Baseline design	649	79	8.2	1219	0	0	0	0	0	0
Best from D/D ratio	511	52	9.8	970	-16	0	20	2	-5	-3
Best from weighted sum	818	109	7.5	1527	4	20	0	0	-2	7

Table 2: Baseline design and optimal designs from using the D/D ratio or the weighted sum as performance function

5.4 Discussion and selection of the final design

The approach from section 5.1 acknowledges that there might not be a unique optimum design, but rather a set of designs along the Pareto front, from which we can select later based on our preferences on how to prioritize one parameter over the other. It makes choosing the final design an engineering decision. The approach described in section 5.2 did not produce the desired results, because using the D/D ratio as performance function is misleading in this case. The approach from section 5.3 is able to deliver a single “optimal” design, although this choice obviously depends on the weights in the performance function. Here, the engineering decision is in the choice of the weights and the performance function. Hence, although the optimization studies provide valuable guidance for selecting the final design, an engineering decision is still required at some point.

It is noted that the values for the horizontal and vertical positions in Table 2 are mostly at the limits of the allowed values, which indicates that a larger range of allowed values might lead to even better performance.

Based on these findings, the best design from the weighted sum approach (as listed in Table 2) was chosen as the final design.

6 Summary and Conclusion

A parametrized geometry from Siemens NX has successfully been used in a design study within STAR-CCM+. The CAD geometry was retained and modified in NX, while the design study was driven by Design Manager in STAR-CCM+. Parameters and geometry were dynamically modified and exchanged through memory using the NX plugin STAR-NX. Three different types of studies were performed in order to gain insight into the design space. The final design was chosen based on a weighted sum of the two objectives as the performance function. With respect to this performance function, the final design performs 25.3 % better than the baseline design.

7 References

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