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A CAD Parameter Based Design Optimization Process for CFD

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Abstract

A design process to improve the coefficient of drag for vehicles analyzed by computational fluid dynamics (CFD) is presented. The proposed design process involves process integration and design optimization of general-purpose optimization software, CFD software, and CAD based morphing software. Since optimizations of CFD, in general, require modification of geometry and node locations, some of the biggest challenges are parameterization and process automation of geometry changes and corresponding mesh regeneration. In addition to this, optimization results need to be incorporated into a final CAD design quickly and easily once the optimization is completed. Therefore, a CAD based morphing tool, allowing direct CAD parameter optimization, is used to re-mesh a CFD model based on the CAD parameters change. Once the process integration is completed, response values are computed at the sampling points using design of experiment (DOE). Then response surface approximation (RSA) based optimization is performed to obtain an optimal solution. Three CAD parameters, which control the front deck of a vehicle, are used as design variables and coefficient of drag (CD) value is optimized to demonstrate the design process. Statistical tools are employed to evaluate the approximation of the response, and the approximated design space of CD value with respect to design variables is visualized in 3D plots to display the design space. The proposed process can provide valuable information and insight into a design space for designers and engineers during early conceptual design stages.

Keywords: *Design Optimization, Computational Fluid Dynamics, CAD parameters, Morphing*

1. Introduction

Fuel economy has become one of the most important quality measures in today's auto industry. Higher fuel efficiency saves consumers fuel expenses, reduces emissions, and can potentially lessen resource consumption and production costs for the industry. Therefore, the auto industry is constantly striving to achieve higher fuel efficiency by designing lighter parts and aerodynamically efficient bodies.

In typical gasoline engine vehicles, for example, the biggest energy loss occurs in the internal combustion engine itself, dissipating as heat, accounting for as much as 63% of total fuel energy [1,2]. The rest of the energy can be converted into mechanical energy; however, it is also lost in aerodynamic drag, electrical, engine cooling, rolling resistance, transmission, power steering, driveline transfer, brake drag, and breaking. Among these disciplines, aerodynamic drag, whose largest contribution comes from exterior vehicle surface, accounts for one of the largest areas of loss, however, it is an extremely difficult area to engineer compared to the other disciplines whose components are mostly invisible to consumers. Since exterior shapes are visible to consumers, conceptual body shapes are mostly derived through cosmetic styling to target specific users. As a result, aerodynamic performance might be largely ignored or might not be an important design consideration. Exceptions to this would be sports cars or some of the highly fuel efficient cars, such as electric and hybrid vehicles, that are aerodynamically engineered from the early design stage. Ideally, however, every platform and model should be optimized to reduce aerodynamic drag. In order to implement this, computational fluid dynamics (CFD) and design optimization should be employed at the earliest conceptual design stages.

CFD is an efficient and relatively inexpensive way to predict aerodynamic drag, pressure distribution, and streamlines of auto bodies, compared to experimental testing. Although CFD used to be a luxury tool for researchers and highly skilled analysts, it has been gradually adapted in routine design processes. It has become easy to use for non-specialists even though the accuracy of solutions needs to be carefully examined. Additionally, recent computer hardware advancement has come to a point of allowing CAE specialists to perform design optimization of CFD responses. The biggest challenges to this can be listed as: 1) parameterizations to perform optimization are not straightforward; 2) parameters to change the discretized models are not easy to reverse map into CAD parameters; and 3) mesh re-generation due to changes in the design parameters needs to be automated. In order to overcome these difficulties, a CAD parameter based morphing tool is used and is integrated into the system, so that CAD parameters are directly optimized as design variables. Therefore, CAD surfaces and discretized analysis model are seamlessly governed by CAD design parameters.

The goal of the proposed design system is to make front-end optimization possible or at least easier instead of performing back-end analyses and optimization. Therefore, CAD designers can optimize aerodynamic responses and study design space at the earliest possible design stages to avoid or minimize the iteration between CAD design and analysis and validation stages.

The rest of the paper is organized as follows: first, integrated system and its individual components, including design optimization and process integration, CAD parameter based morphing, mesh re-generation and CFD analysis, are described. Following that, the design process is applied to reduce the aerodynamic drag of an auto body and demonstrate how the design space can be explored. In conclusion, brief remarks are made.

2. Optimization of CFD responses using CAD parameter based morphing

Unless an optimization module is fully integrated with an analysis module, the process integration must be performed to automate the optimization. Since none of the commercially available CFD software is fully incorporated with optimization, unlike the linear structural optimization area, general-purpose optimization and process integration tools are commonly employed. Figure 1 shows the process flow, shown in the rectangular boxes, as well as data flow, shown in the ovals, in the proposed design optimization process. The design process is also summarized as:

1. Define design parameters (design variables) for design modifications
2. Perform process integration to automate the process of morphing, meshing and CFD analysis
3. Execute DOE analysis and construct RSA
4. Perform statistical analysis to check RSA
5. Optimize the responses and study design spaces

VisualDOC® and VisualScript®[3,4] are used to perform design optimization and process integration, SC/Tetra®[5] is used for CFD analysis and mesh generations, and think3® Global Shape Modeling (GSM)[6] is used for CAD morphing. In the following subsections, each component is briefly reviewed and their roles are discussed.

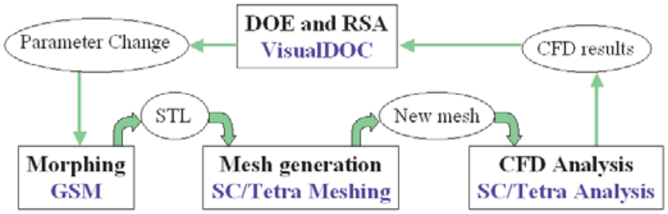

Figure 1. Process and data flow

2.1. Design Optimization

Optimization methodologies are broadly categorized into the following three approaches: (1) DGO, direct gradient (sensitivity) based optimization; (2) RSA, response surface approximation optimization; and (3) NGO, heuristic or non-gradient optimization such as genetic, particle swarm, simulated annealing, etc. Each methodology has its pros and cons and is only suited for certain classes of problems even though there are numerous algorithms within each category. For example, DGO may not be ideal if an analysis cannot provide sensitivity information, requires finite difference, or responses are highly non-linear or noisy functions that may result in undesirable local minimum solutions. However, it is a very effective approach if response functions are relatively smooth and their sensitivity is available. On the other hand, the RSA approximates analysis responses to relatively smooth functions and solves approximated optimization problems. It allows us to visually study design space and provide reasonable solutions with relatively small number of analysis calls for small size optimization problems. If the number of independent design variables is large, the number of analysis calls increase dramatically. NGO is a robust and reliable approach that searches the entire design space globally and does not even require responses to be differentiable. However, it is prohibitively expensive for time consuming analyses since it requires many function evaluations.

In the proposed design process, RSA is used to optimize and study the design space after analysis evaluations are executed at sampling points based on the design of experiments (DOE). DOE, RSA, and design space study are performed in VisualDOC.

2.2. CFD Analysis

CFD is an essential tool to simulate steady/unsteady fluid flow, temporature distributions, diffusion, and other aerodynamic responses. It can apply to a wide range of application problems in construction/environmental, auto body and auto parts, turbo machinery, electronics, appliances, and chemical reactions.

SC/Tetra is used to compute aerodynamic responses of vehicles, such as CD (coefficient of drag) values, CL (coefficient of lift) values, pressure distributions, etc. and its mesher is used for mesh re-generations. Any of these responses can be used for objectives and/or constraints and multi-objective optimization can also be performed to study trade-offs or pareto-frontiers.

2.3. CAD Parameter Based Morphing

In order to perform optimization, a designer must to know which part of the design can be modified and how the design can be modified without interfering with important styling issues. Then, possible modifications need to be parameterized with the smallest possible number of variables. Ideally, the parameters control both native CAD design and CFD analysis in order to transfer the optimization results to the final design. This task is performed in think3's Global Shape Modeling (GSM) API module.

3. Minimization of Aerodynamic Drag

To demonstrate the design process discussed in the previous section, the external shape of an auto body is designed to minimize the coefficient of drag (CD). Figure 2 shows the initial auto body, with the red oval in Figure 2 (left) indicating the design modification area and the red parts in Figure 2 (right) indicating the area affected by the design change. Three parameters, which control the surfaces of the upper auto body, are defined as design variables as shown in Figure 3. The first design variable (DP_TL) and the second design variable (DP_WL) control the bottom center point location of the windshield as x coordinate, and z coordinate, respectively. The third design variable controls the base location of the A-pillar's x coordinate (front to back direction). Table 1 shows the prototype (initial) design variables and design variable bounds.

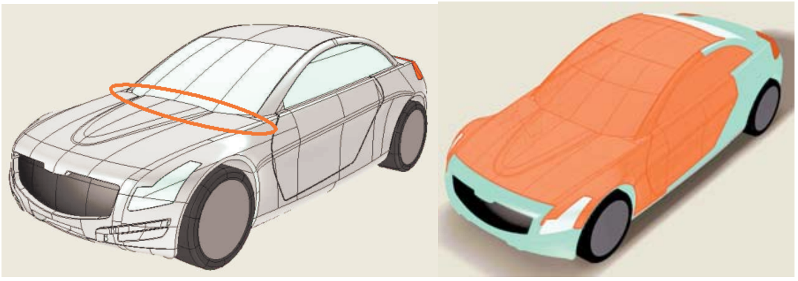

Figure 2. An auto body and design area

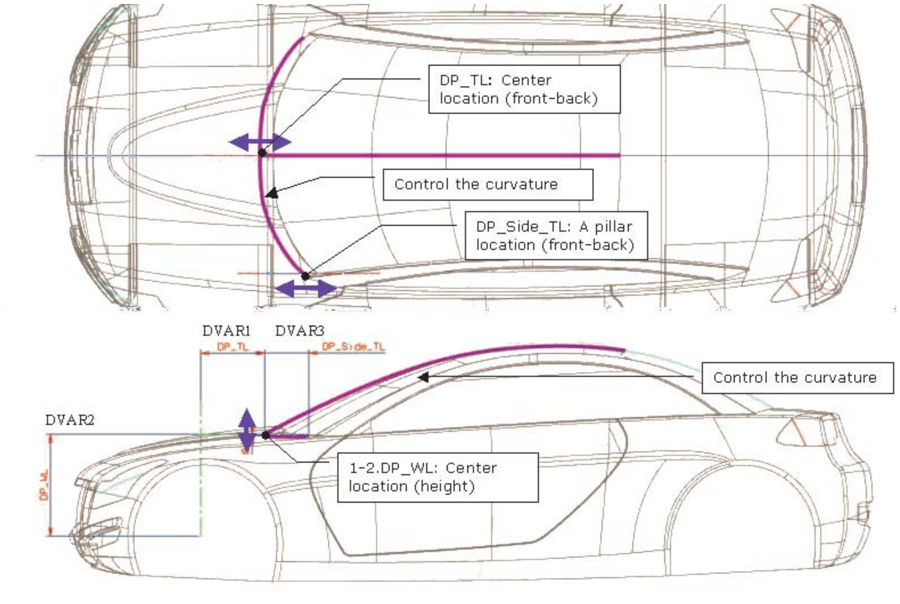

Figure 3. Design parameters

Based on the given bounds, the DOE matrix was constructed using three level orthogonal arrays as shown in Table 2 and CFD analyses were performed at each point. Since a very coarse CFD model (20,000 elements) was used, accuracy of CFD values was sacrificed and higher than realistic values were obtained. Ideally, 10 to 30 million-mesh models should be used for accuracy. The DOE sampling points shown in Table 2 were used to construct an initial RSA model, and RSA based optimization was performed. Two additional searches were performed with updated RSA models and the final solution was verified with CFD analysis. Therefore, the CD value was analyzed a total of 12 times including the initial DOE and final verification runs.

Table 1. Initial, lower and upper bounds parameter values

Design Variable	Lower Bound	Initial Value	Upper Bound
DVAR1(mm)	350	415	480
DVAR2(mm)	530	530	580
DVAR3(mm)	200	240	280

Table 2. DOE sampling points and obtained CD values

DOE Point	1	2	3	4	5	6	7	8	9
DVAR1(mm)	350	350	350	415	415	415	480	480	480
DVAR2(mm)	530	555	580	530	555	580	530	555	580
DVAR3(mm)	200	240	280	240	280	200	280	200	240
CD Value	0.521	0.482	0.439	0.522	0.475	0.489	0.542	0.438	0.495

Table 3 shows the initial and optimum design values, including the predicted (by response surface approximation) and actual (by direct computation from CFD analysis) CD values. 14.3% of drag reduction was obtained in actual CD value with minor design changes as shown in Figure 4. Figure 5 shows the difference between the predicted values by RSA (shown as blue line) and the computed values by CFD analysis (shown by red dots). The final RSA was approximated with full quadratic terms, but relatively small errors were observed.

Table 3. Initial and optimum parameters and CD values

	DVAR1(mm)	DVAR2(mm)	DVAR3(mm)	Predicted CD	Actual CD
Initial	415	530	240	0.5309	0.5224
Optimum	422	557	226	0.4145	0.4473

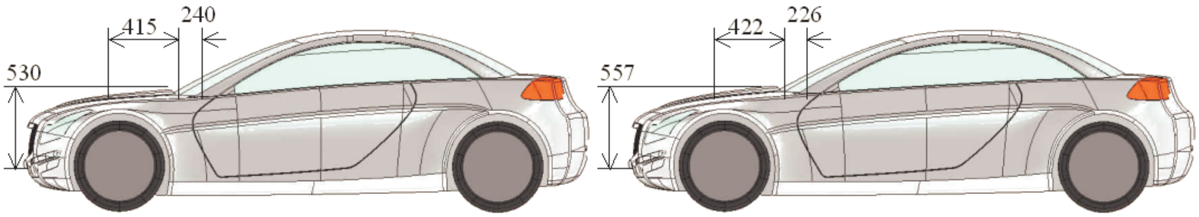

Figure 4. Proto type design (left) and optimum design (right)

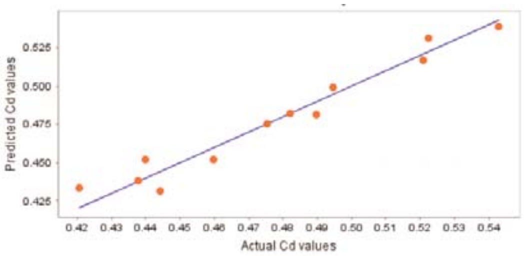

Figure 5. Predicted vs. actual CD value

Finally, the design spaces are investigated using optimization post-processing (visualization) tool. A typical response surface function is expressed in multi-dimensional hyper surface and may not be displayable in a single graph. For that reason, three and/or two-dimensional plots, fixing the rest of variables, are commonly used to view design spaces. Figure 6 shows the approximated CD value surface with respect to DVAR1 and DVAR2, with DVAR3 fixed to optimum value, 226. The surface is redrawn once the value of DVAR3 is re-entered or the slide bar is adjusted to modify the value. As one can see, the surface is relatively flat over change in DVAR2 compared to the change in DVAR1, i.e. DVAR2 is more sensitive to the CD value than DVAR1. The colors of the surface express the range of CD values, e.g. the bottom of the surface in the blue color region has a CD value between 0.4 and 0.44. If the designer wishes to constrain the CD value to be less than 0.44 and choose the objective function to be some other physical value, only the blue region is feasible. The post optimization tools, such as the approximation viewer, could provide useful information on the design space.

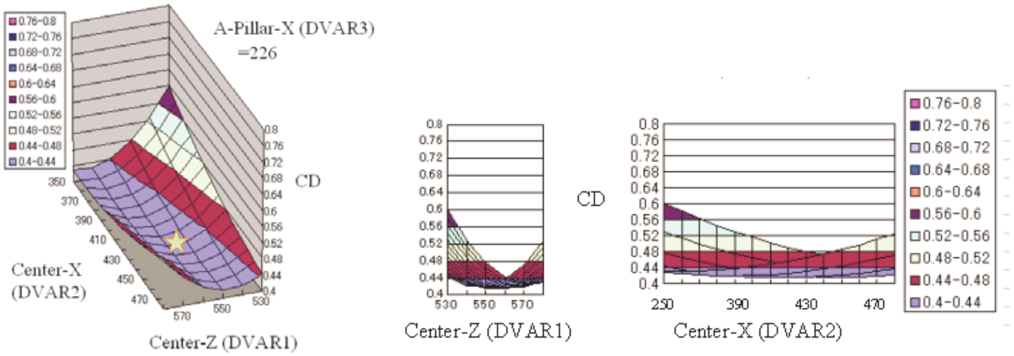

Figure 6. The response surface of CD value

4. Conclusion

The design process to optimize the aerodynamic drag using a CFD analysis and CAD morphing tool was presented. First, the design process was integrated. After RSA was constructed with initial DOE (3 level orthogonal array) points, the optimization was performed using initial RSA. RSA was improved with each design iteration during the optimization process. Finally, the design space was explored with an approximation viewer. The obtained result is very encouraging and the response surface shows valuable insights into the design spaces. The design parameters control both CFD mesh and CAD surfaces; therefore, optimization results can be seamlessly transferred back to CAD design. This makes the front-load analysis and design optimization process faster and easier.

Although only the coefficient of drag (CD value) was minimized as a demonstrative problem, the coefficient of lift (CL value) or pressure distribution can also be optimized simultaneously or separately.

5. Acknowledgement

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References

1. P. Ponticel, "Focused on Fuel Economy," SAE International 22 – 24 March 2010
2. US Department of Energy, http://www.fueleconomy.gov/FEG/atv.shtml
3. VisualDOC Theory Manual Version 6.2, Vanderplaats Research and Development Inc, August 2009
4. VisualDOC Users Manual Version 6.2, Vanderplaats Research and Development Inc, August 2009
5. SC/TETRA Version7 USER'S GUIDE, Software Cradle, Sep 2007
6. think3 version 2008.1 on-line help, think3,Inc.