CAD-BASED OPTIMIZATION AND APPLICATIONS IN AUTOMOTIVE ENGINEERING

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Abstract

The product development in automotive industry is more and more based on computer simulations. Such a development is an iterative process with the following main steps in the loop: modeling of the product with some computer aided design (CAD) tool and then its analysis, which is often of multidisciplinary nature and done typically with a computational fluid dynamics (CFD) or finite element analysis (FEA) software. Based on the results of the analysis, the decision on the CAD model for the next iteration can be done heuristically or by an optimization algorithm. Up to now these steps are comitted separately, typically by separate groups or departments of the team involved in the development. In this paper we introduce our automated optimization method to solve industrial product development problems. This clearly requires first the process integration of several software components and the use of an optimization algorithm and code as the frame of the whole process. One of the main characteristics of our method is the use of parametrized CAD models which enable us to define the design variables as the parameters of the CAD model. Another point is the process integration which requires black-box applications of the CFD or FEA tools, which is still uncommon in traditional engineering. In this paper we introduce the integrated commercial software components and examine their features from the process integration point of view. Then we discuss the characteristics of the optimization methods applied under the circumstances. Finally, we present some results of applications of our method to two problems of automotive engineering, namely to shape optimization of the intake port of a Diesel engine and tolerance analysis of assemblies.

Keywords: multidisciplinary design optimization (MDO), computer aided design (CAD) modeling, computational fluid dynamics (CFD), global optimization, stochastic simulation.

Presenting Author's Biography

Zoltán Horváth received PhD degree in the field of numerical mathematics from the Eötvös Loránd University (ELTE) Budapest, Hungary, 1995. Besides working on numerical analysis for differential equations and optimization methods, he is involved in many applied mathematical projects for industry, particularly on computational simulation of complex fluid flow processes in automotive engineering and global optimization. He is working for Széchenyi István University, Győr and, since 2006, he is the head of Department of Mathematics and Computational Sciences.

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1 Motivation

The starting point of the traditional engineering product development is a prototype of the actual product to be developed further. Following this many steps are executed cyclically starting with tests and measurements on the prototype, then a decision is made on the analysis of test results: to stop or to make a new prototype and continue on the cycle.

This process suffers clearly from the usually large costs of prototype formation and measurements. Moreover, many effects can not be measured efficiently that would be useful for the decision maker. Therefore the need of simulation arises very naturally. Nowadays sufficiently accurate computational simulation tools are at service of the engineers to substitute each steps of the traditional development method: computer aided design (CAD) modeling for prototyping and computational fluid dynamics (CFD) or finite element analysis (FEA) computing for testing. For the sake of safety, the CAD, CFD and FEA steps of simulation ought to be validated by some physical measurements and tests. The simulation in automotive product development has proven so efficient that the recent trend is to supersede the traditional way almost completely (see [11]).

Note that traditionally each step of simulation based development described above is performed by different group of specialists: by the units of CAD modellers' and by CFD and FEA specialists'. Moreover, the CFD and FEA simulations themselves consist of several independent substeps often provided by separate groups; as the most important example to this the meshing of the CAD model can be mentioned. Besides of introducing some delay into the development process the communication between the different groups, the CFD and FEA simulation steps took such a long time up to now that a limited number of optimization cycles could be performed only.

Very recently, the technique and execution time of the simulation steps have reached to such an advanced state that the modeling and its analysis can be integrated into one automated process with tractable evaluation time. By tractability we mean that the evaluation time of the integrated process is not too long hence an optimization method to solve the inherent optimization problem of the product development can be applied with enough steps for the convergence or at least remarkable improvement of the starting value. Most applications with an automated optimization method are based on the mesh morphing technique (see e.g. [12], [1]), i.e. deforming only the mesh at optimization and finally interpolating the optimized mesh somehow to get a CAD model; the latter step implies an unpredictable error and may deteriorate the optimum, we discuss this effect below.

1.1 Scope of the paper

In Section 2 we pose two actual problems of product development and formulate a general problem. Then, in Section 3, we introduce our automated CAD-based optimization method (see also [6]) to solve the problems under consideration, focusing on the simulation aspects. One of the main characteristics of this method is the use of parametrized CAD models which enable us to define the design variables as the parameters of the CAD model. The process integration is taken by almost black-box usage of the CFD or FEA tools, which is still uncommon in traditional engineering. We introduce the integrated commercial software components and examine their features from the process integration point of view. Then we discuss the characteristics of the optimization methods when applied under the circumstances given above.

Finally, we present some results of applications of our method to the problems of automotive engineering posed in Section 2, namely to shape optimization of the intake port of a Diesel engine and tolerance analysis of assemblies. We shall see that our method provides a significant improvements of the objective values comparing to the nominal ones for shape optimization problems and strict tolerance distribution for the tolerance design problem.

2 Problem formulation

To understand better the general problem first we pose two problems from automotive engineering.

2.1 Example 1: Shape optimization of engine components

Design of the shape of engine components to improve the efficiency of the engine is an important task in automotive industry. For example, the shape of the intake port of a Diesel engine has a strong effect on the air flow into the cylinder and the swirl characteristics of the flow inside the cylinder. Roughly speaking, the larger amount of fresh air the better for combustion control whenever we should ensure that the swirl of air belongs to a prescribed interval as a compromise between reduction of soot and NOx in exhausted gas.

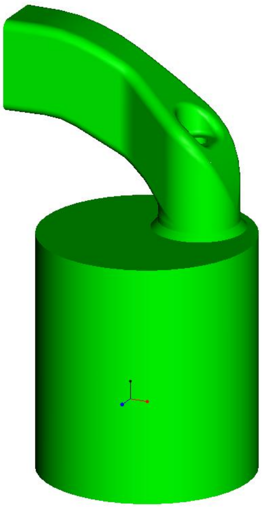

Fig. 1 Diesel engine intake port and the cylinder.

In practice, this intake port development process is simplified into a stacionary problem, namely examination of the steady gas flow under fixed valve lift and fixed pressure drop between the inlet (top cross section of the intake port) and outlet (down cross section of the cylinder). For an actual geometry see Figure 1 where a 2 valve cylinder is presented. Observe that the exhaust port is not modelled here since it is closed during the analysis. Moreover, this port is defined by the engineers as no-swirl port, hence the scaled mass flow rate called α_k (see e.g. [6]) is to be maximized without any restrictions due to swirl, only restricted by other parts of the engine, the water jacket.

In this example the analysis needs flow simulation and the computation of the objective value which is now simply α_k. This requires the usage of a CFD flow modeling software with its preprocessors (e.g. surface and volume meshing software).

2.2 Example 2: Tolerance analysis of complex products

Complex products are usually assembled following a sequential process performed at multiple stations. At each station different components are put together to form the final product. Since each component can be produced with a prescribed tolerance only, the parameters of the final product may suffer from the comitted faults under production.

The main problem to be solved is to determine how the production tolerances of the components effect the parameters of the final product, the assembly.

As an actual example, see a car exterior mirror on Figure 2 and its assembly on Figure 3.

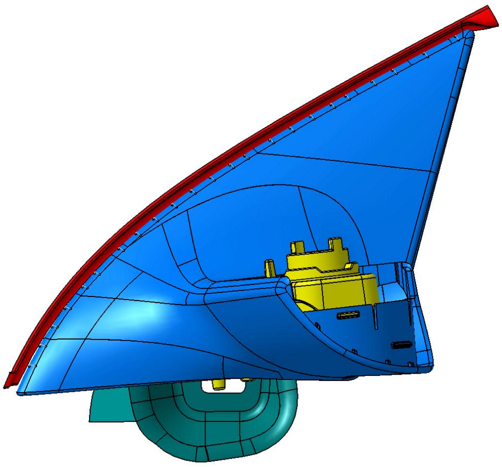

Fig. 2 Car exterior mirror.

Here, on the figures, the red component represent the car-body and the blue part is the hat. The actual problem is that during the assembly process the fitting of small parts are sufferred from production and displacement tolerance errors. Thus the gap between the red and blue parts might be non-uniform although it must be so to satisfy customer demand. Note that the non-uniformness of the gap is computed from measured gap distances at several places as the difference of the maximum and the minimum gap distance. Our problem is to determine the maximum value of non-uniformness of the gap as a function of the tolerances of fitting parts.

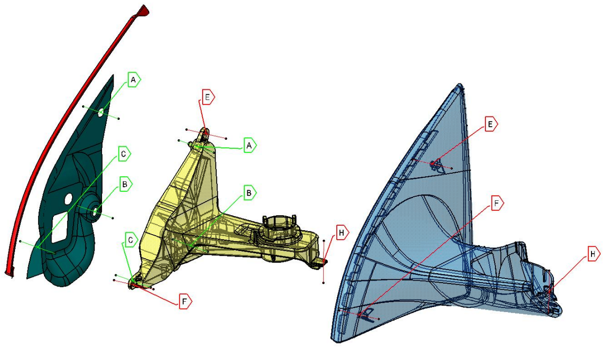

Fig. 3 Assembly of car exterior mirror.

To solve this problem, the usually applied way in engineering is the method of propagated variation (for more sophisticated procedures see [7]). The basic assumption of this method is that the actual values of the tolerance variables are randomly distributed with normal distribution and mean as their nominal value and variations are determined from the production tolerances. Further assumption is that the examined parameter of the final product, i.e. the gap uniformness follows normal distribution around its nominal value and its variation, which is the point to be determined of this method, is calculated by using a simplified, approximate formula of the gap uniformness. Then the maximum of the gap non-uniformness is estimated by using the variance and the six-sigma rule, say.

This widely used method can not be applied to examine complex assemblies because the normality condition of the gap distribution is dubious and the required approximating, simplified formula can not be constructed.

2.3 The general problem

The engineering problems posed above in the previous subsections can be formulated as global optimization (GO) problems.

The design variables are some particular CAD parameters with prescribed a priori given bounds (minimum and maximum values) and possible constraints.

The objective values are determined by the problem and they are defined by computation only. So the structure of the objective function is not known a priori thus no other methods than the GO methods are available in general.

We shall see below how the features of GO are defined in examples given in subsections 2.1 and 2.2.

3 Solution with automated, CAD-based, integrated optimization

In this section we introduce our solution process in details, which was already reviewed in Section 1.

The skeleton is a CAD modeling – Analysis – Optimization cycle that is performed in an automated way where the "Analysis" part splits into Preprocessing (Meshing) and Computation parts.

We had to work out the solution of each step of the cycle as a black-box solver. We remark that in this process we did not use sophisticated CAD-interface like CAPRI ([5]), only the CAD software Pro/ENGINEER ([8]) and CATIA ([4]) themselves. The other components of the integrated system were HyperMesh ([1]) and TGrid ([2]) for the meshing subproblem, Fluent ([3]) for the CFD analysis and several optimization methods, among others LGO ([9]) and for tests genetic algorithms and a memetic particle sworm optimizer ([10]).

The integration is organized so that each process works from file to file, hence the output of each process are files which are the input of the next process.

In the rest of this section we present our method in details and discuss the difficulties and application barriers.

3.1 The frame of the process integration and optimization

The frame program is written in C programming language which runs and manages all the processes and writes the reports on the simulation states. This frame is driven by a simple text file containing information on the input parameters of the integrated software components.

This framework is very flexible. For example, in our second appliation, the tolerance analysis problem, we can decide to find not only the extremal values of the objective variable but also to make a stochastic simulation to find the distribution of the objective value when the design varibles vary randomly according to a normal distribution with mean of the nominal value and variance got from the tolerance values.

3.2 CAD modeling

The CAD model is prepared at the very beginning in a parametric way. This means that it can be be regenerated from a master model with the actual design variables in an automated way, from the frame program.

This part of the integrated process is quite starightforward when a priori a parameric model is given such as in Example 2.2. Then only the lower and uper bounds of the design parameters have to be defined. Sometimes this is not trivial at all because all combination of the parameters in the range to be prescribed has to provide a valid CAD-model; for this systematic and random tests are necessary.

The main difficulty happens to the CAD-modeling step when we have initially no parametric model given. Then a suitable parametric model has to be set up. This is one of the key points of the application of our method: the parametric family of CAD models form the search space of the optimization so it should be rich enough to maintain the possibility of a good optimal value and, on the other hand, it should be accurate enough to be able to capture the shape of the initially given – nominal – non-parametric model. In order to fulfill these demands an experienced CAD modeler is needed.

As an illustration of the material of this subsection, in Figure 4 we presented one parametrization that belongs to Example 2.1. Here the red 3D curve is defined by its projections into coordinate planes and some sections of the intake port are swept along it. The design variables are the parameters of the projected curves and that of the cross sections.

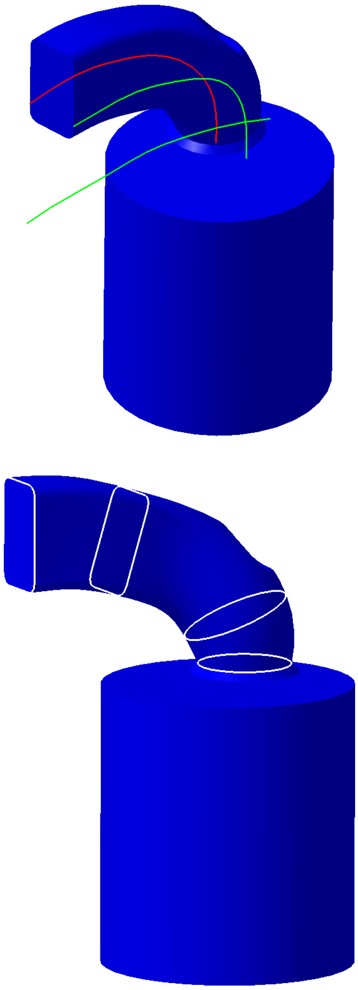

Fig. 4 Construction of the CAD model for the intake port optimization problem.

3.3 CFD analysis

Since the differential equations lying in the background of the flow simulation can not be solved exactly, some approximation method is necessary. Such an approximation requires a subdivision of the flow domain into small cells – this process is called meshing – and the flow variables (pressure, velocity, etc.) are approximated locally on each cell resulting a numerical scheme which is performed by the CFD software.

The CFD calculation computes the objective value for flow driven shape optimization problems. Note that this step is skipped in the frame program when solving the tolerance analysis program.

The meshing and the actual flow simulation processes are driven by some settings to be given before the run of the integrated process. Hence this step is black-box like though in these settings many problem specific experience can be incorported.

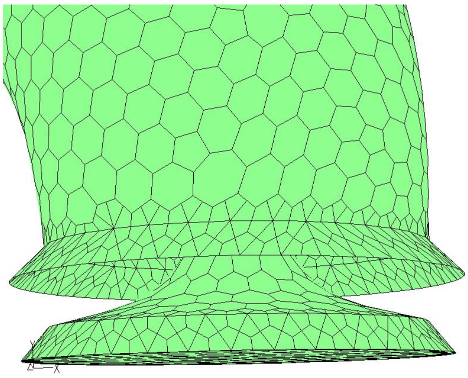

Fig. 5 The hexahedral mesh near the valve seat.

The flow simulation process is the most time consuming part of the whole simulation, typically at least 90% of the total CPU cost is used by CFD. To keep this portion as small as possible we use the novel capability of the CFD software Fluent, the polyhedral meshing. For that a tetrahedral meshing is necessary as were for a normal CFD computation and then a polyhedral mesh is generated which reduces the CPU time at flow simulation to its quarter – although the construction of a polyhedral mesh from the tetrahedral one doubles the time needeed for mesh generation.

3.4 Objective function evaluation

This is problem specific: in Example 2.1 this is done by the CFD analysis process, which computes the flow number α_k, while in Example 2.2 the objective value is computed directly by the CAD process and the frame program.

3.5 Optimization

The optimization algorithm has to face the fact that one objective function evaluation takes at least 20 minutes on an Opteron 2 CPU machine. So, if we want to restrict the total simulation time to 1-2 days, which is the demand from industrial development point of view then only 70-140 function evaluation is possible. For a global optimizer algorithm this is usually not enough for convergence when the GO problem has 5-6 design parameters. We tested many GO algorithms and the memetic particle sworm optimizer [10] has proven the most efficient in our problems.

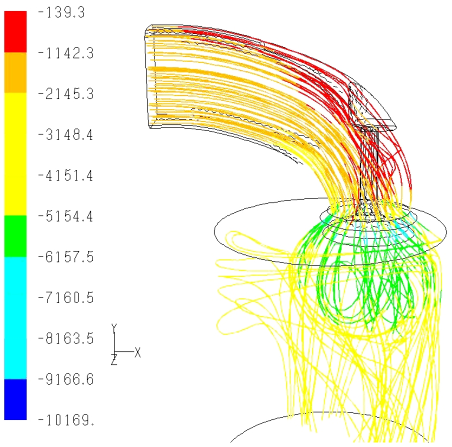

Fig. 6 Pathlines of the calculated flow in the initial flow domain.

4 Results of applications

As we claimed above, we applied our optimization method to the examplary problems posed in subsections 2.1 and 2.2.

4.1 Intake port optimization

The optimization with the memetic PSO code [10] resulted in an improvement of the representative value α_k from 7.9% (flow number of the nominal geometry) upto 8.9% (flow number of the optimal geometry) which is a great improvement. Here we had 6 design variables and to reach this improvement we needed 60 CFD simulation. In Figure 7 the pathlines are displayed emanating from the same point of the inlet as in Figure 6. In order to compare the optimal and the nominal geometries we display Figure 8 where the nominal intake port is colored in blue and the optimal in red.

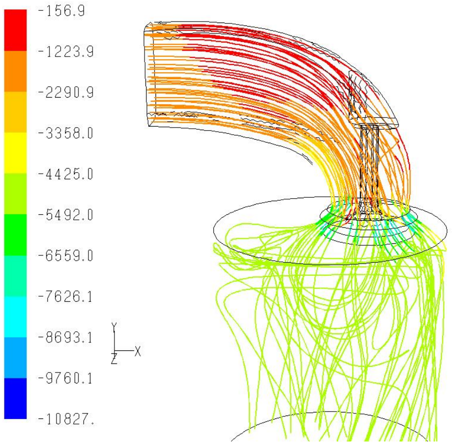

Fig. 7 Pathlines of the optimal geometry (cf. Figure 6).

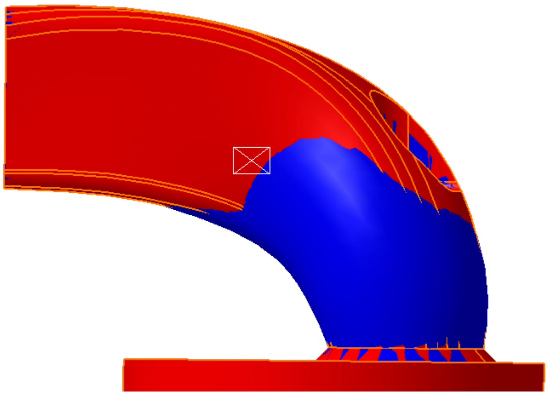

Fig. 8 The optimal (red) and nominal (blue) intake ports.

4.2 Tolerance analysis

In order to find the largest gap non-uniformness value we applied both LGO ([9]) and the memetic PSO ([10]). In this problem one objective function evaluation took 7 seconds and in 90 minutes PSO resulted the optimal value of 0.627 mm and LGO terminated only with a slightly less value.

It might be interesting that in a simulation containing 400 experiments with independent normally distributed values the maximum of the gap non-uniformness value appeared 0.507 so simple simulation could not give back the worst case nor approximately. (Here the variances were chosen according to the six-sigma rule.)

Moreover, the simulation resulted in the empirical cumulative distribution function as well and sensitivity analysis of the tolerance variables could be performed easily.

5 Conclusions

In this paper we introduce an automated optimization method to solve industrial optimization problems related to product development and examine the features of the related software with integrated commercial software components. One of the main characteristics of this process is the use of parametrized CAD model which enables us to define the design variables as the parameters of the CAD model. Thus no interpolation from mesh to CAD is necessary unlike many commercial codes. We applied the resulting optimization sofware to several problems of automotive engineering providing significant improvements in the objective values compared to the initial ones for intake port optimization problem and strict tolerance distribution for tolerance design problem of assemblies. Notice that direct simulation can not give this result back. From the applications we could see that in some cases otherwise excellent global optimizer methods failed due to the special circumstance that only small number of function evaluations are possible. In a future work the optimization could be improved by MDO methods exploiting more the multidisciplinary nature of the objective function evaluations.

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