

Multi-Objective Optimization of a Car Body Structure

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ABSTRACT

In the last years engineers have to deal with multiple, often conflicting targets, where improvement of one quantity leads to deterioration of others, therefore it is impossible to obtain simultaneous structure enhancements without automatic optimizations tools. The so-called trade-offs have to be applied, providing less efficient modifications, nevertheless, for all of the design objectives. The Pareto front is a method that helps to determine a set of equipotential designs.

In order to explore entire design space, response surface methodology supplemented by genetic algorithms is often used. In the work presented, the Gaussian Processes Methodology and an Adaptive Range Multi-Objective Genetic Algorithm - ARMOGA were implemented. Basing on the solutions obtained by the design of experiment, response surface methodology is used to predict the values of the measured outputs throughout the full range of interest. Since only a reduced number of tests is needed, the overall computational time is strongly reduced. Subsequent application of genetic algorithms, provide the possibility of detailed exploration of established metamodels.

In Centro Ricerche Fiat S.C.p.A. an effort of elaborating a novel optimization platform for linking different engineering fields has been undertaken. Noise, Vibration and Harshness, static strength computations, ergonomics and aerodynamics analysis have been coupled in one process, in order to find the most optimal trade-off solutions in Pareto sense during the first phases of the architectural development (early stage design phase).

The main goal of this kind of approach is to increase the product quality, by attaining multiple advances and reduce time-to-market. Simultaneous usage of RSM and genetic algorithm in purpose of conducting optimization, has improved all of the design objectives, keeping the resultant car body shape respect to the ergonomics constraints. Structural modifications were applied by means of the morphing technology, providing changes in the geometry in fully controllable manner.

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INTRODUCTION

Nowadays the automotive design process consists of many steps, that are often conducted by separate specialized groups, in parallel. Their target is to obtain improvements in the line of activity that they are dealing with, what unfortunately often stands in contrary to goals established in other fields. As a good example, ergonomics and aerodynamics approaches can be mentioned, where the former tends to support comfortable large spaces for the driver and passengers, when the later pursue low profile, streamlined car body outline. Many aims of a modern design

process are therefore conflicting, what precludes obtaining intended results in a simple, straightforward approach. Very often improvements provided in one field of interest, lead to deteriorations in remaining groups. Therefore it is of paramount importance to develop optimization tools, able to deal with multiple targets and support the work of multi-disciplinary engineering teams. The early stage design phase is the one that can be supported by this type of procedures and gain the most, due to its flexibility and possibility of introducing significant changes to many parameters, that are meaningful for the mechanical behavior of the structure.

When occurs a need of dealing with many parameters, it is convenient to use methods basing on statistics, due to its capability of managing a large amounts of data in acceptable time. Especially the response surface methods have proved their usefulness and have found their place in engineering. A good overview of this group of approach is provided in [4, 10, 11, 12]. Their usability can be further extended, due to the complementation with the fast converging search algorithms based on the natural evolution theory, the so-called genetic algorithms, which are described in [1,2,3,13]. The abilities of conducting the search in a vast, mathematically complicated domains supported by robustness against the local extremes, assures detailed exploration of a design space and fast convergence to the quasi-optimal solutions. The obtained compromises, as it is the case in multi-dimensional problems, can be screened easily by means of Pareto frontier. A brief explanation of that concept is provided in subsequent section of this paper, more detailed information can be found in [2-3].

The first part of the article provides the theoretical introduction to the problem and the explanation of the objectives and constraints that are taken into consideration. Subsequent part presents detailed information about the optimization path itself and discussion of the results.

OPTIMIZATION PROCEDURE

DESIGN OF EXPERIMENT PREPARATION

The described optimization procedure departs from the Design of Experiment (DoE) [1], that is an approach that allows to estimate the influence of individual design factors on the measured outputs. In addition it provides an ability of determining the level of interactions between the examined quantities, describing the architecture and its behavior, hence facilitates turning any analyzed solution into its robust form. This is possible, thanks to the sensitivity analysis based on the results obtained from the preliminary experiments. In that manner all the weaknesses of the construction can be detected and eliminated, providing higher level of quality.

The first step of the described algorithm is defining the design variables, that can be combined into the design vector $\bar{v} = \{v_1, \dots, v_n\}$ [2]. Those are parameters that are allowed to change their values, throughout the n -dimensional design space. In the presented implementation of the elaborated approach, there were 11 factors that controlled the evolution process of the baseline model, what was the key information in the DoE algorithm selection. Among a great number of possible methods, the most popular choices are the n -level full factorial and the cubic face centered procedures [3]. In both of them, the number of intervals in variation of a single parameter is preliminarily specified, what allows to estimate the amount of solutions needed to complete the experimental phase. The total number of the required numerical simulations is denoted as l^n in the former case, while $l^n + 2n$

+ 1 corresponds with the later. The symbolic values refer to the dimensions of the design space (n) and the total number of each variable's variation levels l (where $l \geq 2$). Basing on the presented expressions, it is noticeable that in the problem stated ($n = 11$), the set of the necessary test solutions would be very large, hence the time needed for the numerical analysis, would be unacceptable.

The overall time needed for one comprehensive simulation of the vehicle's model was close to 15 hours. Because one of the assumptions of the project was to decrease the duration of the concept phase design stage, the number of tested solutions had to be decreased to feasible amount, therefore the so-called reduced factorial algorithm was applied. Its usefulness is especially evident when the design variables' general influence on the modified solution needs to be assessed, without extraction of high-order interactions. With such assumption, the exploration of the design space can be done, using only fractional number of the examination points. As depicted in Figure 1, the main idea standing behind the algorithm is the application of simultaneous changes on all of the design variables and therefore significant computational time savings. In the described approach, the design of experiment consisted of 64 designs, what was sufficient for evaluating the influence of all of the design variables, on the examined model. This number has been chosen in order to meet the industrial time demands on early stage design phase.

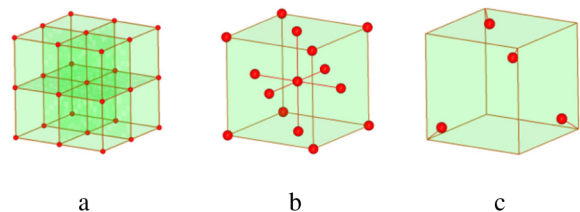


Figure 1. Comparison between the different DoE algorithms for 3 design variables (a - three level full factorial, b - central composite design, c - reduced factorial).

The geometry morphing technique was an instrument of applying structural changes to the finite element model of auto vehicle structure. Detailed information about that approach and examples of application can be found in [4-5]. In brief description, it is a method that allows to change the shape and size of a single component or the whole assembly in fully parameterized way, without further need of redrawing or remeshing the objects. In this manner, the tested solutions have been generated with significant decrease of preparation time, with full control of the process. For the described attempt, the baseline model has been enclosed by the so-called morphing volumes as shown in Figure 2. Thanks to the division into local segments, this 'global box' allowed shape tuning of subcomponents lying in the field of interest, without influencing adjacent parts.

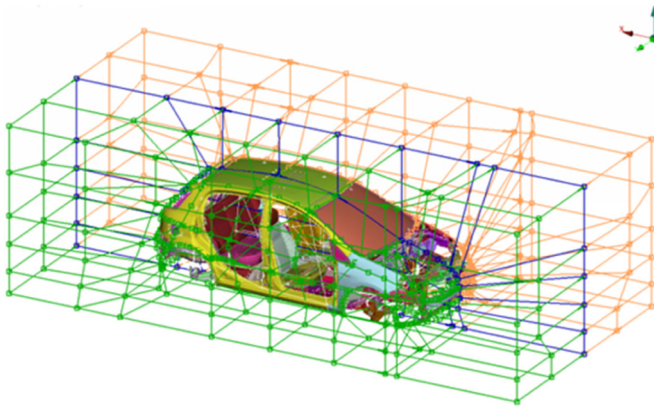


Figure 2. The analyzed FE model enclosed by the morphing volumes.

The prepared set of variables has been specified in order to fulfill the requirements of all the engineering fields taken into consideration during the optimization process. Each of them influenced separate components of the bodywork, by changing their position, curvature or size, together acting on the structure in the most comprehensive way. Since the geometrical modifications are crucial for the body design, it was possible to find parameters affecting all of the objective functions. Among them, there were factors deciding on the position of the upper and lower edges of the windscreen or roof front section vertical position, what altered simultaneously the strength, noise and aerodynamic characteristics of the structure. The example is depicted in Figure 3. Other features, like the spoiler's attack angle, had a major role for improvements in only one discipline.

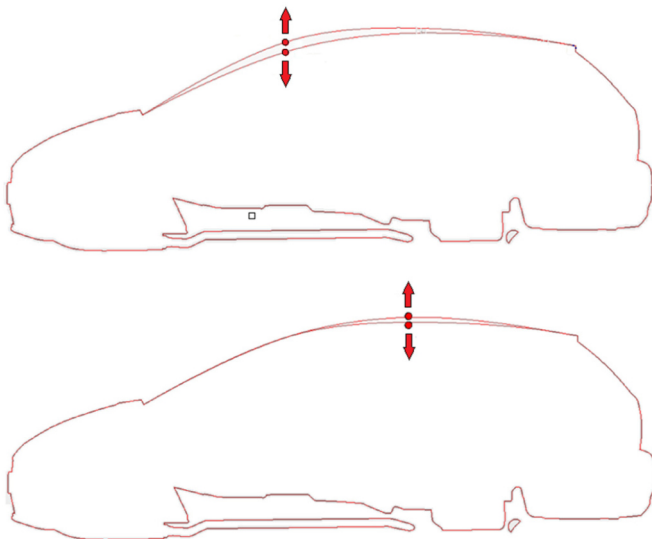


Figure 3. Example of the design variables: windscreen upper edge (upper) and roof middle section vertical (lower) position.

The main principle of the morphing technique is, that it changes only the geometrical position of the grid points of FE

model, without influencing the material properties. If the elements enclosed by the morphing boxes are two-dimensional, also the thickness of the walls remains unchanged. Since body-in-white models of a car consist mainly of the shell elements, panels gauge is not affected.

ANALYSIS OF THE MORPHED STRUCTURES

The subsequent step of the optimization process, after generating all of the required test solutions, was carrying out a number of analysis in purpose of extracting the essential data. As mentioned in the introductory paragraph, the aim was to find simultaneous improvements in different characteristics, which brief explanation is presented in the following paragraphs.

Static Strength

The static strength characteristics of a car vehicle have a significant influence on handling and noticeable impact on other features like crashworthiness, vibrations or fatigue. Therefore an improvement in the static behavior was stated as one of the optimization targets. Torsion and bending coefficients were computed on the basis of the numerical simulations results. They describe the deflection of the structure under specified loads, which have been designed as corresponding with the real operational conditions. The two quantities can be expressed, using well-known [6] formulae, eq. 1.

$$k_f = \frac{F}{\Delta d}; k_t = \frac{M}{\Delta \varphi} \quad (1)$$

Where k_f and k_t are the static strength bending and torsion coefficients respectively, F and M chosen force and torque used for simulating the actual loads acting on a vehicle and finally Δd and $\Delta \varphi$ are the translational and rotational deflections of the structure.

Vibroacoustics

The vibroacoustics analysis are carried out in purpose of estimating the structure born noise level, expressed as a transfer function describing the changes in output quantity, in regard to the input quantity alterations. In case of a car vehicle structure, all the frequency dependent loads are applied in the suspension mounting points and engine bushings, while the measured quantity is defined as the cavity pressure fluctuations. It is measured inside of the cabin, at the positions corresponding to the driver ears [7,8,9]. The comprehensive acoustic analysis consists of inseparable steps, that is: modal analysis of finite element structural and a fluid (inner cavity) models, followed by coupling matrix evaluation. During this stage, the connection between two analyzed models is established, enabling their common interactions, described by equation 2.

This treatment guarantees proper dynamic behavior of adjacent subcomponents, allowing to estimate frequency