

Practical Versus RSM-Based MDO in Vehicle Body Design

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ABSTRACT

Multidisciplinary Design Optimization (MDO) is of great significance in the lean design of vehicles. The present work is concerned with the objective of cross-functional optimization (i.e. MDO) of automotive body. For simplicity, the main goal adopted here is minimizing the weight of the body meeting NVH and crash safety targets. The stated goal can be achieved following either of two different ways: classic response surface method (RSM) and practical MDO methodology espoused recently. Even though RSM seems to be able to find a design point which satisfies the constraints, the problem is with the time associated with running such CAE algorithms that can provide a single optimal solution for multidisciplinary areas such as NVH and crash safety. The present work compares the results of both the methods for a real-world vehicle and concludes that the current practical MDO methodology is substantially more efficient when compared to RSM-based optimization and predicts nearly the same solution as the latter.

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INTRODUCTION

During the past decade numerical crashworthiness simulation for vehicle occupant safety assessment has been greatly integrated into vehicle design process. In addition, simulation-based techniques have led to consistently improved vehicle designs and may have resulted in a reduction in road deaths of over 35%. In order to design and develop a competitive vehicle, metrics related to multiple vehicle attributes including crash safety performance as well as cost need to be considered. However, in today's scenario of threats imposed by global warming calling for drastic reduction in greenhouse gases and need for alternative propulsion systems such as battery-based electric vehicles, designing a vehicle with minimum weight without compromising the prevalent performance criteria has become the most crucial factor in automotive design. Achieving this latter objective requires extensive use of simulation and poses enormous challenges in terms of computation efforts due to

the complex multidisciplinary nature of vehicle design and an endless list of requirements a number of which - particularly belonging to areas such as aesthetics/styling and ergonomics - can be subjective and difficult to capture in a mathematically rigorous optimization approach. There is thus a need for developing efficient MDO (Multidisciplinary Design Optimization) procedures for supporting industrial vehicle product development in a viable way in terms of time and yet leading to meaningful weight reduction perhaps close to a theoretically optimal solution.

The topic of automotive structural optimization has been explored by several authors, e.g. Forsberg and Nilsson [1], Etman [2], and Marklund and Nilsson [3]. Forsberg [1] studied different types of response surface approximations and the relative benefits and drawbacks as applied to automotive impact problems. Some more comparisons of different optimization algorithms can be found in Giunta, Watson and Koehler [4], Gu [5], Jin, Chen and Simpson [6], and Simpson et al. [7]. The majority of the authors used some

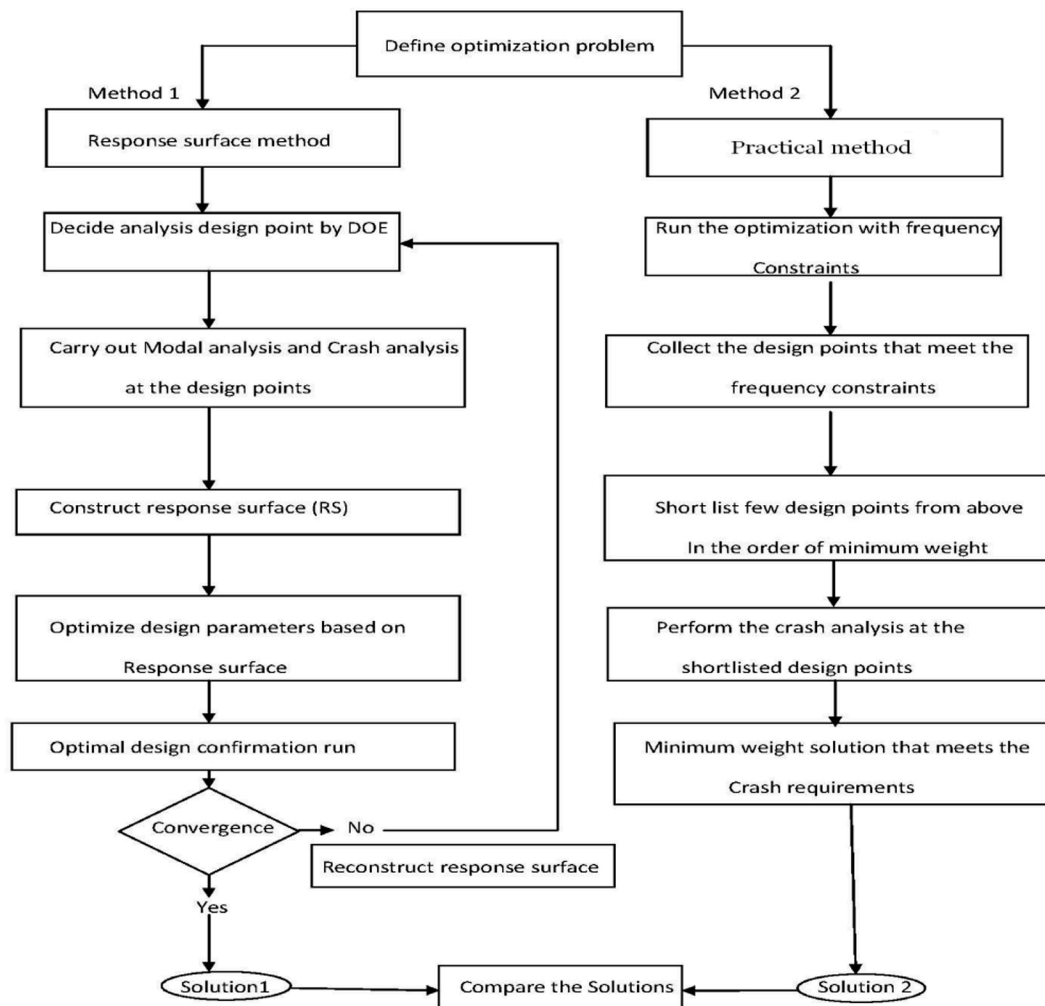


Figure 1. Design optimization algorithms

type of response surface approximation in their work and restricted their studies to a single attribute such as crash safety or durability.

Deb et al. [8], and Deb, Naravane and Chou [9] suggested a practical MDO method that can be applied to weight optimization of automotive structures by specifying constraints on frequency and crash performance. In these papers, references to work reported by other investigators pertaining to MDO in vehicle design can be found. The present work further substantiates the practical MDO approach by comparing results obtained from it with the mathematically more rigorous response surface method (RSM) by considering the finite element model of a real-world vehicle. The present modified practical MDO approach is shown to be as accurate as the RSM-based MDO generally followed while being computationally efficient by a large margin making it a viable candidate for vehicle weight optimization with a realistic set of design variables and constraints imposed by multiple attributes such as NVH (noise, vibration and harshness), durability and crash safety.

RSM-BASED AND PRACTICAL MDO APPROACHES

For simplicity, the current work deals with multidisciplinary optimization of an automotive front body structure using finite element analysis considering essential crash safety and NVH performance parameters such as peak deceleration in an NCAP crash pulse and lowest modal frequency. To this end, the front structure of a commercially sold car is optimized using two different approaches, namely, the conventional RSM-based weight optimization technique and a practical weight-reduction method. Both the methods are described in a flowchart in Figure 1 and compared in detail in subsequent sections. It can be seen in this figure that while Method 1 involves iterations and use of response surfaces for speeding up predictions for design points, Method 2 is a one-pass sequential procedure which relies on finite element analysis directly for weight reduction.

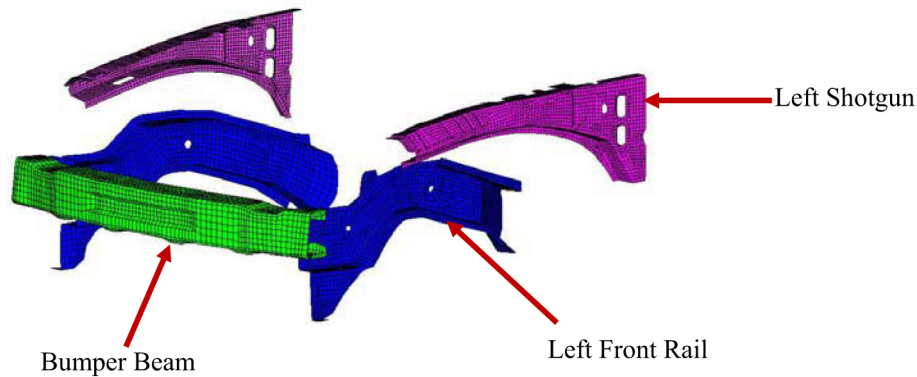


Figure 2. Front body components selected for optimizing mass

IMPLEMENTATION OF RSM-BASED OPTIMIZATION

According to the conventional RSM-based approach, response surfaces are at first generated for predicting both NVH and crash performances. To construct these response surfaces, a set of design points is chosen using a DOE (design of experiments) technique and modal frequency analysis using OptiStruct and crash analysis using LS-DYNA is carried out. The response parameters expressed as a function of design variables are the lowest modal frequency and peak value of crash pulse. Additionally in the present study, a response surface for prediction of mass with respect to design variables has been found to be most useful. It has been verified that this response surface accurately estimates the total mass of the parts the gages of which are the design variables chosen. Using the lowest natural frequency of the front end and peak deceleration extracted from the NCAP crash pulse as constraint parameters, gages of bumper beam, front rails and shotguns as design variables, the mass of the front end structure (i.e. effectively the total mass of the parts mentioned) is optimized. Functions based on traditional gradient-based search algorithm in MATLAB are used for optimization. A convergence check is then performed to confirm the optimal design.

It is noted that the optimization of a baseline vehicle is carried out in the implementation of the RSM-based approach. The constraints for optimization are such that the lowest modal frequency and peak deceleration in a full-frontal NCAP test simulation will not deteriorate while obtaining the optimal solution. The optimization problem is specifically stated as follows:

Objective function for minimization: Mass of the vehicle front end

Design variables:

- (i). $1.4 \text{ mm} \leq T1$ (thickness of front bumper beam, Figure 2) $\leq 2.2 \text{ mm}$;
- (ii). $1.4 \text{ mm} \leq T2$ (thickness of front rail parts, Figure 2) $\leq 2.2 \text{ mm}$;
- (iii). $T3$ (thickness of shotgun parts, Figure 2) = 1.6 mm (assumed as constant as the peak deceleration was found to

be minimally sensitive with respect to changes in gages of shotgun)

Constraints:

- (i). Lowest (first) modal natural frequency $\geq 15 \text{ Hz}$;
- (ii). Peak deceleration $\leq 43G$

As mentioned earlier, the design points for creation of the desired response surfaces were selected using a DOE-based technique. Since there may be nonlinear interactions between the factors and the responses being measured, a Central Composite Design (CCD) [10] approach that could model curvilinear relationships between inputs and outputs is chosen. Twenty cases were identified for generating the response surfaces as shown in Figure 3; the results obtained after analysis are given in Table 1. It is noted that all three design variables given in the statement of the optimization problem above are varied for arriving at the response surfaces. Table 1 actually contains fifteen unique cases for determination of modal frequencies and NCAP crash pulse using a truncated finite element model, with same mass as the original full vehicle model, later outlined.

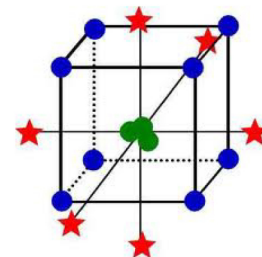


Figure 3. Distribution of design points ($T1$, $T2$, $T3$) according to a CCD scheme (6 points with stars are outside the given domain, 8 points are at the boundary corners and 6 are within the domain)

With the aid of Minitab statistical analysis package and data given in Table 1, second order polynomial response surfaces are generated for the two constraint variables i.e. lowest natural modal frequency (ω) and peak value (α) of