

An Iterative Application of Multi-Disciplinary Optimization for Vehicle Body Weight Reduction Based on 2015 Mustang Product Development

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ABSTRACT

Designing a vehicle body involves meeting numerous performance requirements related to different attributes such as NVH, Durability, Safety, and others. Multi-Disciplinary Optimization (MDO) is an efficient way to develop a design that optimizes vehicle performance while minimizing the weight. Since a body design evolves in course of the product development cycle, it is essential to repeat the MDO process several times as a design matures and more accurate data become available. This paper presents a real life application of the MDO process to reduce weight while optimizing performance over the design cycle of the 2015 Mustang. The paper discusses the timing and results of the applied Multi-Disciplinary Optimization process. The attributes considered during optimization include Safety, Durability and Body NVH. Several iterations of MDO have been performed at different milestones in the design cycle leading to a significant weight reduction of the already optimized design by over 16kg. Some examples of additional MDO studies optimizing parts of the Body structure for performance improvement or additional weight savings are also provided.

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INTRODUCTION

Designing a vehicle body involves satisfying multiple, often conflicting requirements related to safety, durability, NVH and other attributes. Multi-Disciplinary Optimization (MDO) is a way to develop a weight efficient design that also optimizes vehicle performance with regard to attribute targets.

In the recent years the Multi-Disciplinary Optimization has become a well-established optimization method as the computer speed increased, the simulation methodologies matured, and specialized MDO software tools have been developed. A number of successful applications have been reported in the area of crashworthiness optimization [1], [2], [4], [9], [11], [12], [15], NVH and durability optimization [3], [5], [9], [10], [13] and reliability and robustness optimization [6], [7], [8], [14]. A considerable amount of research is currently devoted to improving the MDO process by perfecting the techniques for creating meta-models [16], inventing new optimization algorithms [20], as well as developing the efficient optimization strategies [17], [18], [19].

Multi-Disciplinary Optimization is a tedious process. A typical vehicle Body MDO involving Safety, NVH and Durability attributes requires performing several thousand CAE simulations with many of them taking more than 10 hours to complete. Until recently it has been difficult to utilize MDO in the design cycle to provide a design direction in a timely manner. However, as the computational power has increased and specialized MDO tools have become more efficient

the time required to complete MDO iteration can be significantly reduced. It is now possible to perform MDO iteratively, several times during the design development. This is essential since a design evolves in course of the product development cycle which can invalidate previous results but also provides new opportunities for weight reduction.

This paper presents a real world application of MDO for optimizing weight while maintaining performance over the design cycle of the 2015 Mustang. Three MDO iterations have been performed, the first one early in the design cycle focused on the performance improvement, the second one during the Underbody design development phase, and the third one during the Upper Body design development phase. In this paper the second and the third MDO iterations are presented. Multiple additional MDO studies have been performed aimed at improving performance of critical parts of the Body structure thus leading to a better overall outcome of the subsequent whole Body MDO iteration. Two examples of such studies are briefly described in this paper.

MDO TIMING IN FORD PRODUCT DEVELOPMENT

MDO is currently embedded in the Ford Product Development System. Multiple MDO iterations are performed at different milestones of the product design matching two major milestones in the design cycle: the Underbody design phase and the Upper Body design phase.

The first iteration is performed early in the Program timing. At this point any part (except for carry-over parts) can change in terms of geometry, material grade or gauge. Both Underbody and Upper Body are optimized using shape, gauge and material grade optimization. Chassis and other systems can be included to exploit the synergies between major systems.

The second iteration is done when the Underbody design is being finalized (Underbody Phase MDO). The gauge and material grade variables are selected for both Underbody and Upper Body. Shape variables can be selected for Upper Body. After this phase the Underbody parts are frozen. Their gauges can still change slightly within $\pm 10\%$ range.

The last iteration is performed when the Upper Body design is maturing (Upper Body Phase MDO). At this point the parts geometry is already frozen so only gauges and material grades are included as design variables. The Underbody parts gauges can still be included but with upper and lower bounds within 10% of their baseline values.

In addition to three major MDO iterations additional MDO studies can be performed to improve performance or provide additional weight savings.

MDO PROCESS

MDO starts with the selection of attributes and load cases to be included in optimization. Typical attributes included in vehicle Body optimization are Body NVH, Safety and Durability (other load cases can be included as needed). For each attribute multiple performance metrics are assessed during CAE simulations. The typical number of performance metrics (responses) included in Body MDO is between 100 and 200.

The next step is the selection of the design variables. These can include gauges, material grades, shapes, topology variables, weld pitch or other properties. Design variables are selected based on sensitivities, animations, strain energy contour plots and engineering judgment. The selected design variables are reviewed to exclude carry-over parts, those affecting performance for load cases not included in the current MDO etc.

The MDO process described in the paper used Response Surface Method based on Meta-models generated after running DOE (Design of Experiment) CAE simulations. A typical vehicle Body MDO requires performing several thousand CAE simulations with many of them taking several hours to complete. The MDO software tools provide numerous algorithms for generating a response surface such as Radial Basis Functions, Gaussian Process, Evolutionary Design, Kriging, Polynomial and others. Usually several algorithms are tried out to select the best one for a particular response.

Cross-Attribute optimization is based on meta-models. The performance targets are included as constraints during optimization. Commercial MDO software such as modeFrontier provides many optimization algorithms. Frequently used in Body MDO are MOGA (Multi Objective Genetic Algorithm) and NSGA (Non-dominated

Sorting Genetic Algorithm). Based on meta-models up to 100,000 designs are evaluated in course of optimization. Trade-off curves (Pareto Front) are generated between the weight and critical performance metrics. Several virtual designs are selected from the Pareto Front and validated through CAE simulation.

UNDERBODY PHASE MDO ITERATION

In course of the 2015 Mustang development the Multi-Disciplinary Design Optimization was performed three times. The first one early in the design development was focused on performance improvement. The second iteration was done on the mature Underbody and Front/Rear Subframe designs with a goal of optimizing the gauges to identify weight saving opportunities. The optimization was a system level MDO involving Vehicle Safety, Body NVH, Full Vehicle NVH and Chassis NVH /Durability. The load cases included in MDO are shown in [Figure 1](#). The total number of responses representing performance metrics exceeded 130. Given the large number of responses as well as the confidentiality of the related data no specific information related to the responses will be provided in the paper. All the responses were constraint at targets based on pre-MDO discussion. The optimization was set up to reduce the weight while meeting the performance targets. There were 109 design variables, out of which 66 were related to Underbody. The Underbody parts whose gauges were selected as design variables are shown in [Figure 2](#).

Overall the optimization identified the weight saving opportunities of 8.8kg for the Body, 1.5kg for the Rear Subframe while the weight of the Front Subframe remained unchanged. Since the focus of this paper is Body optimization the further details will be provided for this part of the results.

Out of 8.8kg of Underbody weight saving proposed in the optimized design, 7.5kg was implemented in the next release of the design. The recommended gauges for 6 parts were not implemented due to geometry changes, stamping feasibility and a need to improve the baseline performance. The optimized setting for the Underbody gauges is shown in [Figure 3](#). Within 66 Underbody design variables, 29 were decreased ([Figure 3a](#)), 8 were increased ([Figure 3b](#)) and 29 were left unchanged ([Figure 3c](#)). The overall distribution of the gauge changes is shown in [Figure 3d](#).

The parts with gauges increased in optimization ([Fig. 3b](#)) provide valuable information about the area of the structure that needs enhancement. The structure can then be improved by geometry changes instead of gauge changes which are usually more weight efficient. For example, based on this input ([Fig. 3b](#)) the Tunnel Reinforcement (see [Fig. 13](#) for description of the Body parts) was redesigned and with a more efficient geometry the gauge of this part was reduced in the next MDO iteration ([Fig. 8d](#)). Similarly, adding darts to the Reinforcement Apron Front Fender Lower increased its stiffness and allowed for reducing the gauge of this part in the next iteration of MDO ([Fig. 8a](#)). Comparison of the parts with gauges reduced and increased in optimization ([Fig. 3a](#) and [3b](#), respectively) shows that the gauge of Reinforcement Apron Front Fender Upper was reduced while the gauge of Lower part was increased. An

example of improving weight efficiency of a structure while maintaining the same performance. A significant number of design variables (29 out of 66) were left unchanged. It indicates that they were at the optimal setting for the current architecture and performance targets. However, in optimization problems with large number of design variables it can happen that some of the design variables are not changed because the optimizer stops at a local minimum rather than at a global minimum [17]. MDO software tools (modeFrontier, i-Sight) are capable of identifying global trends and relations between design variables and responses based on DOE runs (Main Effects, Student Significance Charts, Correlation Charts). Further analysis of these trends can provide an insight into which design variables are critical for particular targets and which ones are irrelevant. This can help identify design variables that have a negligible effect on performance but have a potential for reducing weight. Including irrelevant design variables in optimization increases a chance of reaching a local instead of global optimum.

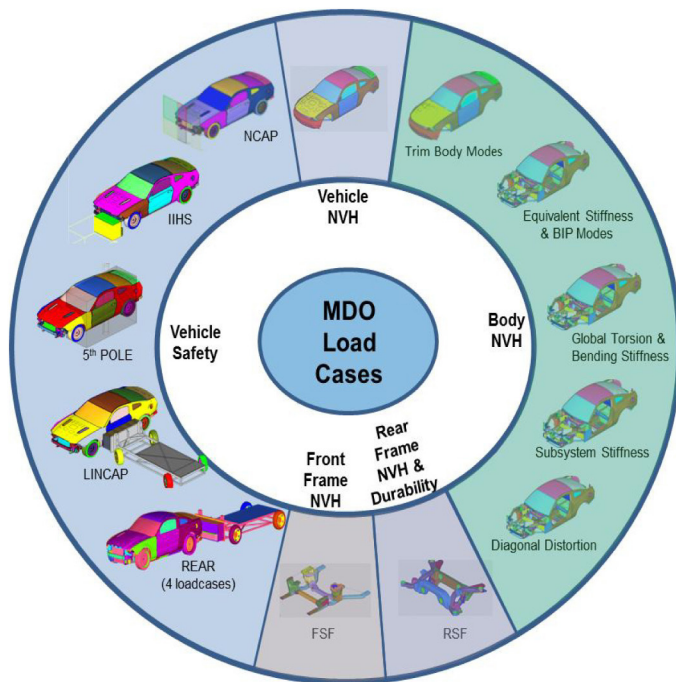


Figure 1. Underbody Phase MDO - Load Cases

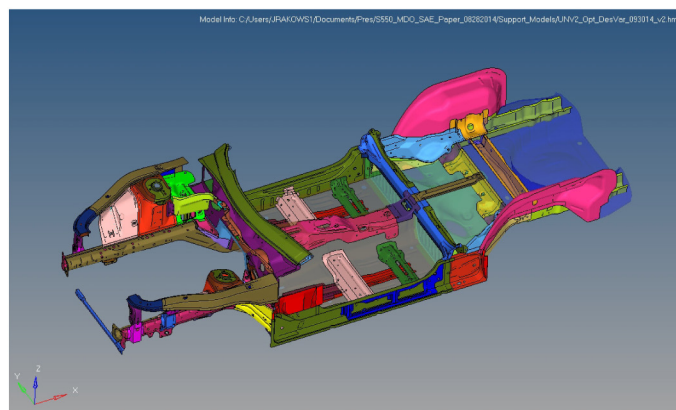


Figure 2. Underbody Phase MDO - Body Parts with gauge selected as Design Variables

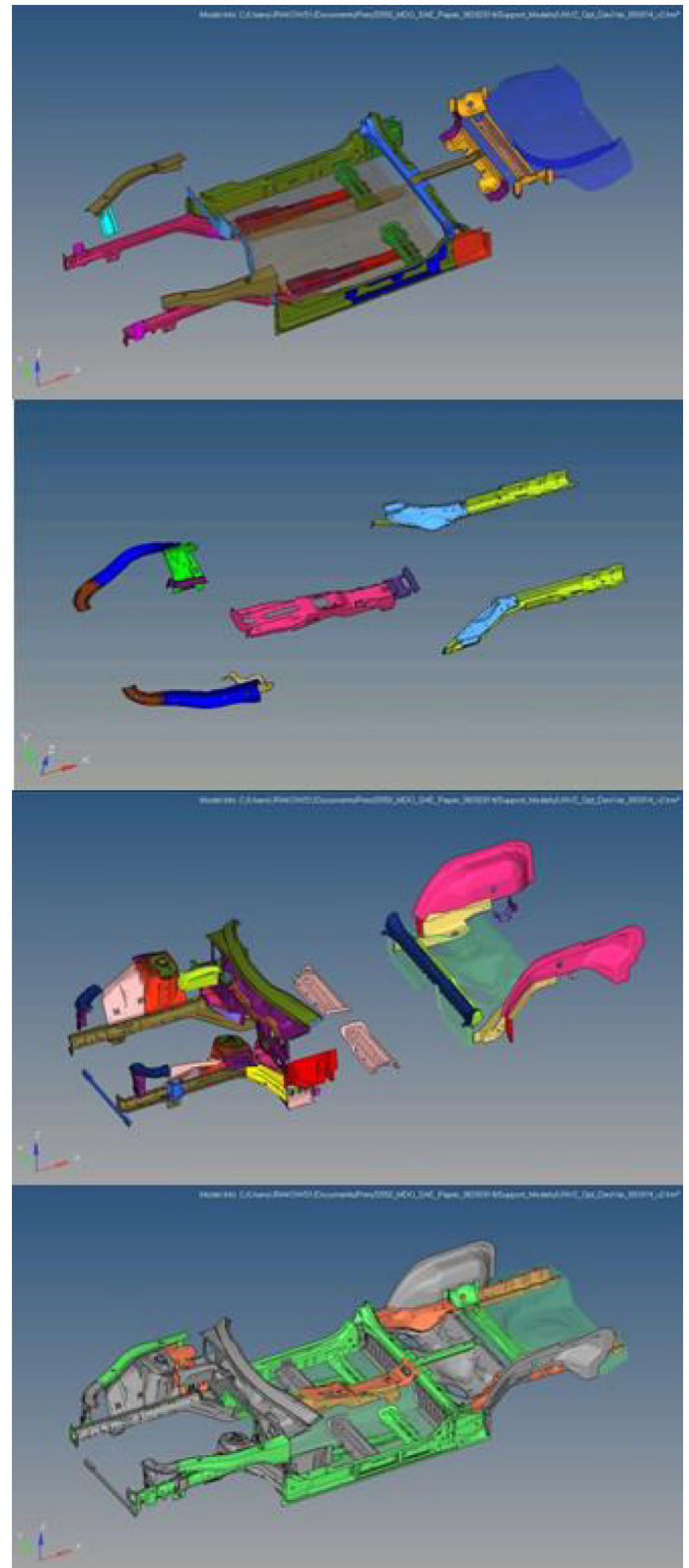


Figure 3. Underbody Phase MDO - Optimized Setting: (a) Parts with gauges reduced in optimization; (b) Parts with gauges increased in optimization; (c) Parts with baseline gauges; (d) Overall gauge changes (red - increased gauges, green - reduced gauges)