

PSO-Based Multidisciplinary Design Optimization of Automotive Assemblies

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ABSTRACT

Widely used in automotive industry, lightweight metallic structures are a key contributor to fuel efficiency and reduced emissions of vehicles. Lightweight structures are traditionally designed through employing the material distribution techniques sequentially. This approach often leads to non-optimal designs due to constricting the design space in each step of the design procedure. The current study presents a novel Multidisciplinary Design Optimization (MDO) framework developed to address this issue. Topology, topography, and gauge optimization techniques are employed in the development of design modules and Particle Swarm Optimization (PSO) algorithm is linked to the MDO framework to ensure efficient searching in large design spaces often encountered in automotive applications. The developed framework is then further tailored to the design of an automotive Cross-Car Beam (CCB) assembly. Sensitivity study is performed to identify the major contributor parts to the CCB mass and performance. The optimized CCB is shown to meet the design requirements while the mass and cost are considerably reduced.

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INTRODUCTION

The drive for using light materials in vehicles can be better comprehended in the light of the ever-toughening regulations on fuel economy and green house emission standards. Original Equipment Manufacturers (OEMs) continue to strive for improved fuel economy and lower emissions through investing more in lightweight structure design. Heavier parts of the car such as body, engine, seats, and wheels were the first to receive weight reduction but lightweight design has now found its way to smaller components such as instrument panel and windows [1]. Aluminum alloys, Magnesium alloys, Carbon Fiber, and Polymer Composites are all used quite often by OEMs. Aluminum can be processed in several ways and has a relatively low melting point. Thanks to its high ductility, aluminum products are typically formed fairly near to the end design, eliminating the need for costly post-processing operations [2]. Weight reduction in vehicles can be of primary or secondary nature. The primary weight reduction is the direct reduction of the body weight as a consequence of using less material in the vehicle components. A secondary weight reduction can then be accomplished in the engine, drive train, and chassis since the lightened vehicle needs lighter supporting frames and less power to propel. Substituting steel and cast iron with Aluminum and Magnesium ones not only leads to weight reduction but also allows for addition of many safety and luxury features at no mass penalty and potentially offers superior crash characteristics [3].

Historically, part development in automotive industry used to be done based on trial and error on physical prototypes. Nowadays, however, CAE tools have taken over this process for the most part, making numerical simulation of parts fully integrated into the product

development cycle [4]. Automotive metallic components are typically developed from concept to the final product in numerous iterations. For a new concept design (one which is not built upon existing ones) the first step is to determine the topology of the component based on certain loading conditions, geometric and manufacturing constraints, available package space, performance requirements, and an initial material candidate. The design is then further refined in shape optimization stage by smoothing curves and sizing holes and openings, as well as adding various reinforcements and shape features (e.g. ribs, fillets, beads, flanges, dents, etc.). The goals of this stage are to improve the performance, ensure manufacturability, and meet the package and clearance requirements more closely. In the case of thin-walled structures such as stampings, a gauge design step is also typically involved in which the wall thicknesses are revisited to minimize the weight while the performance is retained. This hierarchy of design decisions remarks the sequential design approach in which different aspects of the part are decided upon in separate and serial steps. Naturally, at the end of each step of this approach, only a sub-space of the initial design space is transferred to the next step, limiting the latter steps to exploit the design space to its fullest. Traditionally, the effort has been on finding a feasible solution and optimization of an aspect of the system or product has been done independent of the rest, therefore, the need to update and adjust the design based on the that aspect.

Multidisciplinary Design Optimization (MDO) [5] employed in this study is a methodology for design of complex systems. In a design scenario where multiple analyses are involved and the outcome of one analysis influences the others, this methodology offers systematic and simultaneous handling of the interaction and promotes better use of the design space, leading to shorter design cycles. An MDO

architecture is realized by splitting the complex system into subsystems, referred to as disciplines or modules, and managing the hierarchy of the design decisions and interactions between the subsystems in a structured fashion. Each module of the MDO handles one or more aspects of the design. Particularly in automotive engineering, the potential of MDO has been recognized but its integration into the product development cycle is yet to be achieved. Apart from being computationally expensive, the bigger challenge is the need for MDO to suit the company organization and existing product development infrastructure. Examples of recent case studies of MDO in automotive includes NVH and crashworthiness [4], vehicle body design [6,7,8], and CCB assembly design [9]. The MDO framework presented in this paper comprises of disciplines based on the three material distribution techniques used in traditional lightweight design, i.e. topology, shape, and gauge optimizations, and is powered by PSO stochastic search algorithm to ensure exploration of the design space in an efficient and effective scheme. In terms of the paper layout, the following section is dedicated to the detail description of the developed framework. The MDO framework is further tailored for optimization of an aluminum Cross-Car Beam (CCB) assembly in the section after. Next, the results of the CCB optimization and a discussion of the results are presented and concluding remarks forms the final section.

MDO FRAMEWORK FOR AUTOMOTIVE LIGHTWEIGHT DESIGN

Design of complex systems poses major challenges to the designer due to multiple disciplinary analyses being involved, hence, specialized design tools and strategies will become indispensable in such cases. A complex system is one that its detailed function, including the collaboration between subsystems, cannot readily be perceived. The complexity of a system arises from having many subsystems or from numerous interconnections among subsystems. Although having interaction between subsystems complicates the optimization process of such system, the synergy among the subsystems can be fully exploited through these interactions [10,11].

MDO architectures can be categorized to single-level and multi-level architectures. In single-level architectures the design decisions are solely made by a single optimizer. They use a non-hierarchical structure to manage the interactions between the disciplines. Multiple Discipline Feasible (MDF), Individual Discipline Feasible (IDF), and All-At-Once (AAO) are well-known single level architectures. Multilevel architectures on the other hand transfer the non-hierarchical relationship among the disciplines into a hierarchical structure. Each level of the optimization will have its own optimizer, with commonly having one system level optimizer to manage the responses of all disciplines. Concurrent Subspace Optimization (CSSO), Bi-level Integrated System Synthesis (BLISS), and Collaborative Optimization (CO) are among multilevel MDO methods [11,12,13]. Selection of the best MDO architecture for a given problem is done in an ad hoc manner. However, considering a number of factors is often beneficial. An imperative factor is the existing coupling between distinct disciplines of the problem. Capability of implementing the legacy tools already in use is another key metric in selecting the right architecture. The transparency of the algorithm is also a driving factor when

multiple architectures can be applied to the system. This factor considers the ease of understanding and ability to extend the mathematical model behind the method [10,12].

Inspired by the steps involved in the traditional design approach, an MDO framework is constructed consisting of three modules, each of which makes use of one of the material distribution methods, i.e. topology, shape, and gauge optimizations. The state-of-the-art CAE tools are well capable of applying these methods; however, these methods are traditionally employed independent of one another and in a sequential fashion. Choosing a suitable MDO architecture in this case can foster the parallelization of this steps and betterment of the final design. The Multidiscipline Feasible (MDF) architecture employed in this work is particularly useful for this purpose as it preserves the product development organization of the OEM, including the CAE packages already in use in the conventional manner. The inherent link between the modules in this study also supports this choice, since all three material distribution methods are altering the stiffness and mass of the structure, which are responsible for the NVH response. In the MDF architecture all of the system analysis is managed by a system analyzer. In an MDF analysis, a complete system analysis is performed in each iteration and communication with the optimizer is done after the system responses are obtained. That is, the entire problem is seen by the optimizer as a normal optimization task while inside the system analyzer the subsystems are required to reach consensus. The presented framework based on MDF architecture is fairly transparent and easy to tailor and extend to other standard automotive analyses. In the following sub-sections the MDF modules are described.

Part Module

The part module enables the framework to use alternative designs for specific parts in an assembly. When several topologically different design concepts are available for a component in the assembly, the design space is significantly expanded compared to the case of having only one design for each part and limiting the design variables to only shape changes and gauge modifications. Two different cases of part modification are employed in the part module. The first one occurs when a part is added to or removed from the assembly. Optional parts are occasionally used in an assembly for the purpose of stiffness or strength boost. Such parts are not essential to maintain the integrity of the assembly and rather are tied to one or more components to carry a portion of the loads or add to the overall stiffness. Although contributing to the performance, the optional parts impose extra costs and manufacturing effort, as well as add to the mass of the assembly.

The second scenario addressed in the part module is to deal with alternative designs for a component based on topology optimization technique. The aim of topology optimization is to find the optimum layout of the material which possesses the lowest mass while satisfying the imposed requirements. Using Solid Isotropic Material with Penalization (SIMP) method and FE discretization, a quantity designated as element density is assigned to every material element. These element densities are the design variables in the topology optimization. A zero density for an element is interpreted as having a void at that position. Contrariwise, a density equal to unity means material is present at the location of the element. Intermediate

densities can be interpreted as void or material based on the designer's judgment, although in practice elements with densities larger than 0.3 are typically seen as material. To alleviate this ambiguity, intermediate densities are penalized according to the power relationship $\hat{K}_i(\rho_i) = \rho_i^q K_i$ in which K_i and $\hat{K}_i$ are original and penalized stiffness matrices respectively and $q > 1$ is the penalization power. It is shown that for problems with active constraint on the volume, choosing a sufficiently big value of q (usually $q \geq 3$) results in a fairly 0-1 distribution pattern [14].

Topology optimization tools utilized for the conceptual design of the parts can provide a first-order idea of the material distribution in the package space; however, the results can often be interpreted in multiple ways and topologically different designs may be proposed based on the topology optimization outcome. The part module thus expands the design space by offering multiple designs for a given component. That being said, in this work we assumed that the interpreted shape is feasible for stamping and no provisions for casting parts are considered. However, it will be possible to expand the part module to intelligently select the manufacturing method based on the result of the topology optimization.

Shape Module

The shape module is responsible for shape modifications of the parts. With the topology of the part being preserved, shape changes such as scaling, adding reinforcing beads, and adding flanges are introduced into the design in this module. Furthermore, the flexibility offered by real-time morphing tools and implicit parameterization techniques can be employed to explore a wealth of alternative shapes. For instance, cross-section shape optimization [15] using implicit parameterization is supported by this module. The designer needs to create shape variables using the morphing capability and add it to the shape module as a design variable. Parameterization reduces the number of design variables greatly although the final shape will be influenced by the choice of candidate shapes. Non-parametric shape optimization methods capable of preserving the initial curvatures and using all nodes as design variables can address this issue [16] but is part of the current framework.

Since the topology of the assembly remains intact during the shape optimization, these shape changes maintain the integrity of the assembly while tuning the design to meet the required performance targets. Two types of shape changes are employed in the present module. The goal of the first one is to shrink the cross section of the tubes; therefore a lighter and cheaper tube may be obtained. The second shape modification increases the stiffness of the parts by introducing bead patterns. Bead patterns are essentially protrusions or corrugations in the direction perpendicular to the surfaces; hence it is shape optimization in the third dimension [17]. Beads are capable of improving bending and torsional stiffness through increasing the moment of inertia of the section. Bead optimization has been largely applied to plate structures [18] to improve vibration and acoustic properties. A particular example of such structures is automotive floor panels which have been successfully optimized in Ref. [19]. Topography optimization has been employed to lower the cost while retaining the stiffness of sheet metal brackets as well [20]. In the present work too, the location and shape of the bead is determined

based on shape optimization performed on each candidate part separately. The topography optimization problem solved for each candidate part can be stated as:

$$\begin{aligned} \max F(\vec{x}_p) \quad , \quad wrp. \quad \vec{x}_p \\ \text{Constraints: } \begin{cases} \text{Bead width} \geq b \\ \text{Bead draw angle} = \theta \\ \text{Bead height} \leq h \end{cases} \end{aligned} \quad (1)$$

in which $\vec{x}_p$ is the position vector of point p on the part and F is a property of the component (e.g. stiffness, natural frequencies) to be maximized. This optimization procedure ensures that the beads are located in the most effective areas of the component. Through introducing beads that are wider than b , have draw angles of θ , and not higher than h , the topography optimization guarantees that the proposed shape change is feasible to manufacture and packable in the design space. In cases of overlapping beads or beads that cross the boundary of the components, the designer has the option to add constraints to the topography optimization. However, none of these cases pose a challenge to the optimization work, given that proper manufacturing constraints are applied in this module. Bead length is not constrained in this study, since a long bead can always be broken into two smaller ones to accommodate the requirements. Note that the result of the topography optimization will be reviewed and adjusted by the designer before being fed to the framework.

Once the bead layout is determined, all shape changes are saved as a list of node perturbation vectors based on the discretized finite element mesh of the model. Upon calling the shape module, it starts to calculate the new coordinates of the nodes based on Eq. (2) in which $\vec{X}_{new,i}$ and $\vec{X}_{org,i}$ represent the current and original position vectors of the i -th node in the global coordinate system respectively.

$$\vec{X}_{new,i} = \vec{X}_{org,i} + \alpha_j \times \vec{V}_i \quad (2)$$

Parameter α_j is the design variable designated as Shape Coefficient of j -th part which is chosen independently for each part by the optimizer and $\vec{V}_i$ is the perturbation vector applied to the i -th node. This method of modifying the design ensures that the integrity of the finite element mesh is preserved.

Gauge Module

The gauge module controls the thickness of thin-walled parts. Thickness can be incorporated as a design variable in the design of parts made by stamping and some of the extruded parts with constant thickness throughout the length (e.g. tubes). While the part and shape modules determine the topology and detail features of the parts, the gauge module explores the design space by altering the thicknesses. Here, only discrete gauges in accordance with typical sheet metals are made available for the module to choose from. As a possible extension, it would be interesting to allow this module to choose the gauges from a continuous range. However, the focus of the present framework is strictly on stampings and extrusions with pre-determined gauge libraries.

Integration of Modules with the Optimizer

The described modules form the MDF analyzer which is capable of evaluating a design specified by the global and local design variables. The global design variables such as material properties are shared by all modules. The local design variables are Shape Coefficients X_s (varies between 0 and 1), part numbers X_p (discrete values corresponding to alternative designs), and gauge values X_g . The MDF analyzer is then linked with an optimizer to complete the MDO loop.

Dealing with large complex systems such as automotive and aerospace structures, the common situation is to confront discrete, non-convex, and non-differentiable design spaces. In such occasions the global stochastic methods are suitable since they do not rely on the sensitivities of fitness and constraint functions. In this work, Particle Swarm Optimization (PSO) method is selected as the optimizer for the MDO framework. The PSO approach is to utilize multiple agents (referred to as particles) to move the entire swarm of solutions towards optimality. The adaptation of the swarm to the environment guides the particles to return to the promising regions found and search for better solutions over time [21].

The proposed MDF framework can tackle different automotive and aerospace design tasks by employing the existing CAE technology and insights from the legacy design procedures. For a specific design task where multiple aspects of the design need to be considered, each aspect can be implemented as a distinct discipline and the suitable solvers can be employed to obtain the required system responses. In the following section, the design of an automotive assembly known as Cross-Car Beam (CCB) is addressed using the proposed framework. The CCB design showcases the implementation of the MDO and verifies the capabilities of the framework in the design of complex structures.

IMPLEMENTATION OF THE MDO FRAMEWORK FOR CCB OPTIMIZATION

The Instrument Panel (IP) complex is a collection of modules each responsible for an aspect of control and safety of the vehicle. The skeleton of the IP is a metallic supporting structure designated as the Cross-Car Beam (CCB) assembly. Figure 1 illustrates the CCB assembly of a midsize passenger car. The CCB Tube, steering column support brackets, knee bolster supports, end brackets, airbag supports, and cowl top are normally included in the assembly. The CCB forms the load path to transfer the weight of the IP and steering column to the body and chassis through its junctions with the car body. It also absorbs the crash forces, preventing the occupants from experiencing severe impact forces.

Traditionally, CCB components are built from mild steel. The majority of the components are stamped sheets; however, the tube(s) is commonly manufactured by extrusion. The components are assembled by means of laser and Metal Inert Gas (MIG) welding. Similar to many assemblies in vehicles, aluminum CCB tends to substitute the steel counterpart thank to the excellent energy absorbance and lower weight of aluminum alloys. The primary challenge pertaining to aluminum CCB is its significantly high cost which is roughly twice the steel CCB cost for a midsize car.

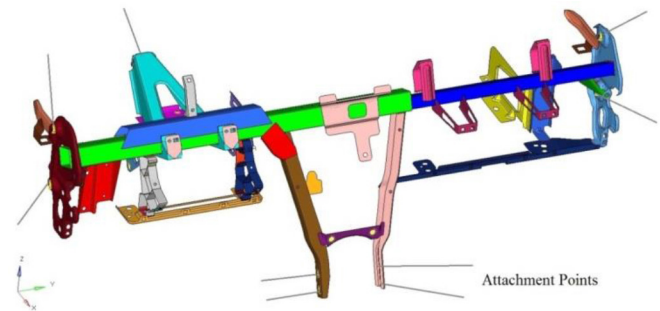


Figure 1. CCB assembly of a mid-size car. Straight lines designate body attachment points.

The principal constraints in the design of CCB assembly are Noise-Vibration-Harshness (NVH) and crashworthiness performances. The NVH criteria ensure that natural frequencies of the structure are securely detached from the frequencies of prevailing excitement sources. The engine, power transmission system, and the road surface are common sources of vibration. High-amplitude vibration resulted from overlapping of natural frequencies with those of the excitement sources creates significant annoying noise both inside and outside the vehicle. The vibration can be transmitted to the steering column and cause discomfort and distraction for the driver as well. Apart from making the occupants uncomfortable, high-amplitude vibrations diminish the lifespan of the vehicle components. To keep the noise and vibration of vehicles in a standard range, OEMs follow NVH regulations which should be fully fulfilled before a new product is released. The crashworthiness target deals with the ability of the structure to absorb undesirable forces in the event of crash. The airbag support absorbs a significant portion of the energy and plays a vital role in protecting the occupants. The knee bolsters are also critical in protecting driver's knees in a collision. Failure to absorb adequate energy causes the knee bolsters to move upward and come in contact with the steering column. Consequently, this situation allows the steering column to rotate and remove the airbag from its proper orientation, jeopardizing the safety of the occupants [22].

There are limited number of studies on the design and optimization of CCBs in the literature. Lam et al. [23] performed material and gauge thickness sensitivity analysis on a mild steel CCB. The study aimed to replace the mild steel in the CCB with aluminum and magnesium alloys. The thickness of the shell structure is altered by 10% increment in each step up to 40%. The crash performance of the CCB is investigated through side and knee impact analyses. It is shown that increasing the thickness of the components by 40%, results in the same crashworthiness behavior as the baseline steel model. Thickness modification by 10% increments is a fairly crude approach for finding the optimum gauge values. Following the conventional sequential design approach, the NVH and crash analyses are performed independently; hence the full capacity of the design space is not exploited. There, the natural frequencies are not used as constraint for the optimization problem and rather act as a check to verify the NVH performance. Tawde et al. [24] reported sensitivity analyses and weight optimization of a CCB assembly. They have described Design Sensitivity Analysis (DSA) methodology to help with identifying components that can be improved. In the NVH analysis, the components which are likely to contribute to the crash performance