Topology Optimization in Automotive Brake Pedal Redesign

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Abstract— Nowadays, automotive industry is continuing to strive for light weight vehicle in improving fuel efficiency and emissions reduction. To produce a better performance car it is important to design vehicles with optimum weight. In order to reduce the weight of vehicle without sacrificing its integrity, this project aims to employ topology optimization technique to propose an optimal design of an automotive component in early phase of product development. In this project the material used for an existing brake pedal is unchanged as this study focuses on reducing weight of existing brake pedal without material substitution. The digital model of an existing brake pedal was generated using CATIA V5 solid modelling software. Topology optimization was performed by using Altair Optistruct software under linear static stress analysis. Finally, a new light weight design brake pedal is proposed. The result of the study shows that the weight of a new designed brake pedal was 22% less as compared to an existing brake pedal without sacrificing its performance requirement.

Keyword- Brake pedal, Redesign, Topology optimization, Weight reduction

I. INTRODUCTION

Nowadays, automotive industry is growing exponentially towards light weight vehicle, cost effective vehicle components and environmental friendly. Vehicle weight reduction is one of the promising strategies to improve fuel consumption. By reducing vehicle mass, the inertial forces that the engine has to overcome when accelerating is less, and the work or energy required to move the vehicle is decreased. In general, for every 10% reduction in vehicle weight, the fuel consumption of vehicles is reduced by 5-7% [1]. There are three common approaches to minimize vehicle weight in practice that are; substitution with light weight material, downsizing of the vehicle and removing unwanted material from the structural component. Traditionally, brake pedal is designed by iterative methods and optimized under non-optimal topology in static load conditions. This approach requires various iterations and the final design is arrived through via trial and error approach. This iterations process is time-consuming therefore increased cost. In addition the output of this approach does not necessarily represent the best design solution. Thus a systematic approach to reach optimal design solution in the conceptual design stage is vital and it can be realized with the application of topology optimization. This paper presents the application of topology optimization to redesign brake pedal of passenger car aims to for weight reduction. The approach has twofold; accelerate the process and achieve the optimal design solution.

II. LITERATURE REVIEW ON THE APPLICATION OF TOPOLOGY OPTIMIZATION

An important aspect in automotive industry is to achieve better design concepts by considering structure performance and manufacturing cost in the early stages of product development. Topology optimization is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance target or predetermined design goal. It provides an initial design concept for downstream applications, which leads to achieving better design by using computer-aided techniques. Yildiz et al. [2] employed topology optimization approach for optimal design of engine mount bracket under dynamic loading conditions. The research aims to create an initial design concept, which has optimal structural layout. The effectiveness and verification of proposed approach were demonstrated with experimental results. Cavazzuti et al. [3] have solved the problem of automotive chassis design in view of weight reduction by means of topology optimization. They found that the methodology has been proven to be successful in finding innovative and efficient layouts for automotive chassis. Kaya et al. [4] completely redesigned a failed clutch fork using topology and shape optimization approach. A new design proposal was determined with the topology optimization approach and response surface methodology was used to improve the design of clutch fork. The improved design of clutch fork was obvious as the mass reduction was 24% and maximum stress reduction was 9%. In addition the rigidity was improved up to 37% in comparison to the original clutch fork.

Weight reduction is a major issue for car maker companies due to the need to comply with the emission regulations without reducing the vehicle safety. A classic trial-and-error approach to design in the automotive industry is becoming inadequate and new means are needed to enhance the design process. A major improvement on weight can be achieved by adopting suitable optimization techniques from the early design stage. Wang et al. [5] obtained the layout of the initial design proposal of the frame based on the basis of topology optimization, with the weight was substantially reduced while the performance enhanced. Topology optimization was able to produce reliable and satisfactory results with the verified structural model [6]. They produced a new bracket shape based on the topology optimization result and later on this result was compared with the initial concept model. Significant increment which is 14% of the first natural frequency of new bracket with only 4 % mass increment increased was achieved and 31 % mass decreased compared to the base model without the increment of stress under gravity load cases. It was analysed that a new bracket would not fail during a vibration durability test, and these results were verified with a fabricated real sample under the durability condition.

Despite the commercial topology optimization tool, the topology design problem can be formulated as a general optimization problem and solved by the mathematical programming method. Yang and Chahande [7] developed an in-house topology optimization software, TOP, used to analyse automotive components. Three automotive examples including a simplified truck frame, a deck lid, and a space frame structure were carried using the developed software. They found that the conceptual proposals can be obtained and the overall mechanical design process can be improved substantially in a cost effective manner. Cavazzuti et al. [8] have presented a methodology for automotive chassis design in involving optimization techniques. The methodology was applied to the design process of a rear-central engine high performance vehicle chassis. The objective of the optimization process is the chassis weight reduction, yet in fulfilment of structural performance constraints as required by Ferrari standards. The results demonstrate that there is a significant weight reduction when compared to the chassis of the Ferrari F458 Italia. Costi et al. [9] have presented a methodology to reduce the weight of an automotive hood substructure. The methodology consists in a loop of different optimization techniques, i.e. topology, topometry, size and topography, coupled with a constant re-designing of the model. Without breaking the performance targets expected by Ferrari internal regulation, the mass has been reduced respecting manufacturing constrain. Boonpan and Bureerat [10] have proposed an efficient design process for an automotive component consisting of three design stages. The design stages consist of compliance minimization (topological design), eigenvalue maximization (topological design), and detailed design. The design parameters include mass, compliance, natural frequency, Frequency Response Function (FRF), stress, displacement, buckling, and fatigue life. The three-stage design was implemented on the synthesis of an automotive part. The mechanical part obtained by using such a design strategy was compared to the original design that is currently in use. It was found that the new part, using the proposed design approach, is superior to the original component based upon static and dynamic performance.

III. APPLICATION OF TOPOLOGY OPTIMIZATION IN BRAKE PEDAL REDESIGN

Traditionally, brake pedal is often designed by iterative methods, optimized under non-optimal topologies and often based on static loading conditions. The following optimization stages were carried out to obtain the optimal layout of material in brake pedal redesign.

A. Stage 1: Define the Initial Design Space and FE Model

To begin the topology optimization process the amount of volume that the geometry can safely occupy that is known as the design space was determined. It represents the volume that will be meshed into finite elements and iterated upon while the optimization algorithm is working. In addition any space that needs clearance for being iterated during the optimization was determined as non-design space so that the software does not try to use that space for load-bearing elements. In the case of brake pedal the hole for the pivot shaft and brake pedal pad were set as non-design space and represented in blue colour in Figure 1.

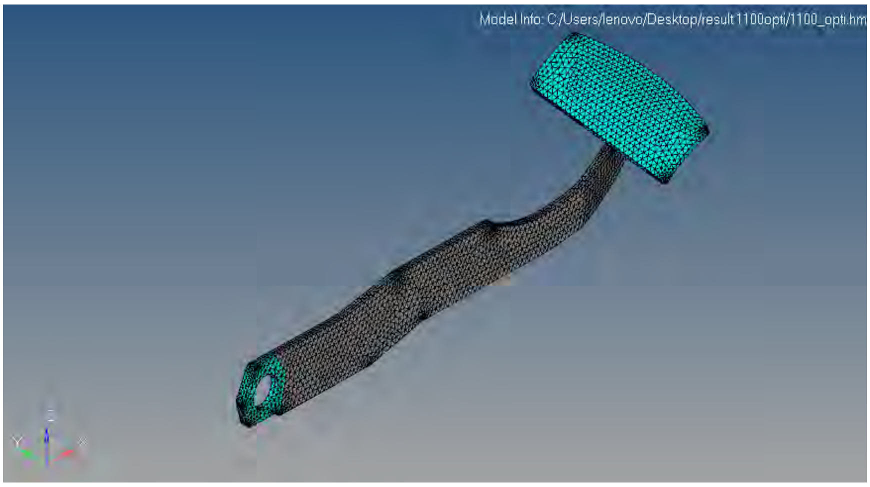


Fig.1 Design space and non-design space of brake pedal

The design space previously created in a CAD program was imported as an IGES (Initial Graphics Exchange Specification) file and the geometry was “cleaned” to prepare for meshing. This means that some of the lines in the imported model were toggled from edge lines to suppressed (or manifold) lines so that they would not represent an artificial edge. Once the geometry was cleaned, the design space volume was filled with tetrahedral elements using the auto-mesh features of HyperMesh. This was done with a volume-tetra element with a nominal minimum size of 8mm, feature angle equal to 30° and element size is 4. The 3D element quality check was applied to check the quality of mesh. The warpage, aspect ratio, skewness and jacobian were set into 5°, 5, 60° and 0.7° respectively. The mesh quality was acceptable as only 5% errors were found. Youngs’s modulus (E), Poission’s ratio (ν) and density (ρ) for the material of brake pedal is taken as 2.1×10^5 MPa, 0.3 and 7.9×10^2 kg/m^3, respectively and classify as isotropic. The load applied on the brake pedal pad was a normal 1100 N force with maximum allowable displacement is 10mm [11].

B. Stage 2: Topology Optimization

The objective function of any optimization problem is to minimize or maximize a certain response while meeting a prescribed set of constraints. For this it is necessary to program the software to solve for the desired responses, and then choose limits to these responses. In the case of the brake pedal optimization, the set objective function was to minimize the mass while maintaining its integrity. Obviously the mass minimization cannot be continued without limit, thus it is necessary to define responses that have upper and/or lower limits as constraints. For the design of brake pedal the Von Misses Stress must be below the material yield stress as to obtain minimum safety factor 1.5. In addition the maximum displacement is 10 mm.

The topological optimization procedure consists of following main steps:

Step 1: define optimization functions
Step 2: define objective and constraints
Step 3: initialize the optimization parameters
Step 4: execute the topological optimization
Step 5: review the results.

In this case study, the density of each element is selected as the design variable and above given steps is carried out using Optistruct software. A finite element model of topology after material removed from brake pedal is given in Figure 2.

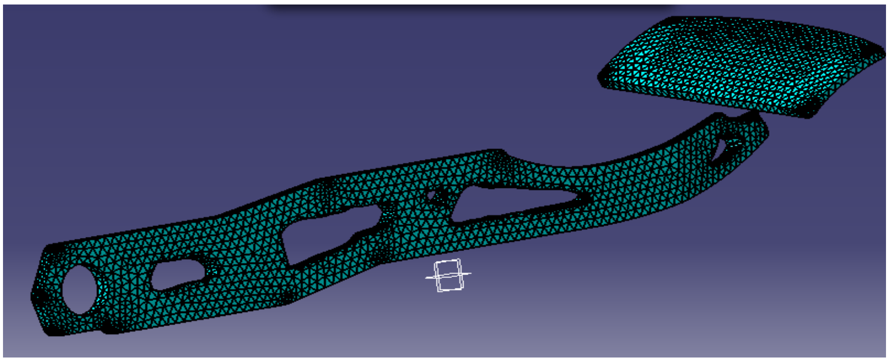


Fig. 2 Finite element model of brake pedal after topology optimization

C. Stage 3: Material Removal Process

The optimization process took 45 iterations to remove the unwanted material from the design space. The optimization was run on 3.3 GHz 15 4 processor 2 GB RAM and it takes 46 seconds for convergent. Although the topology result appears reasonable, obviously the design is definitely not ready for production. Thus the result of topology optimization was redefined based on material distribution as in Figures 2. Some interpretation was required to create the final design. The geometry was opened in a CAD environment as the Optistruct has the ability to export the topology results as IGES file using an export future. The optimize shape after interpretation was created using CATIA V5 software is shown in Figure 3. There are some considerations in interpretation step or the engineering knowledge that was considered to interpret new design from topology results. For example, appropriately sized fillets were utilized to reduce stress concentrations and to aid manufacturability using standard tooling. The design retains the feature proposed by OptiStruct such as the holes in the pedal arm and retains the material between the pedal arms to the pedal pad.

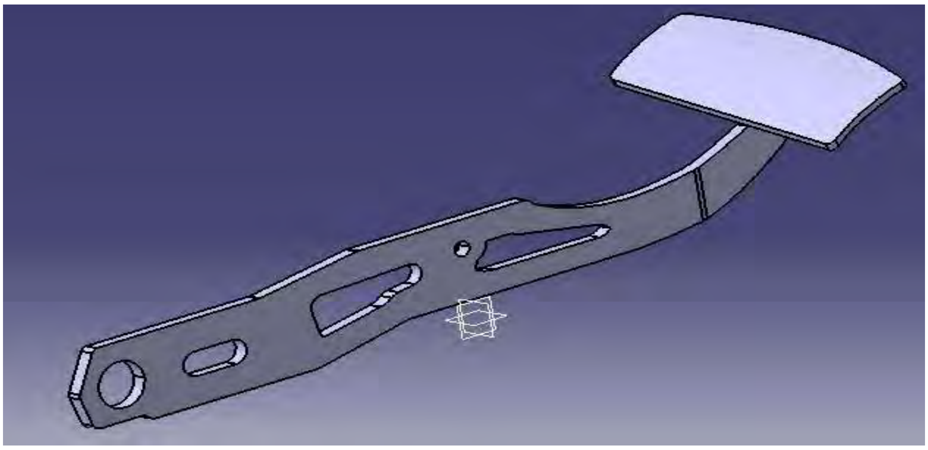
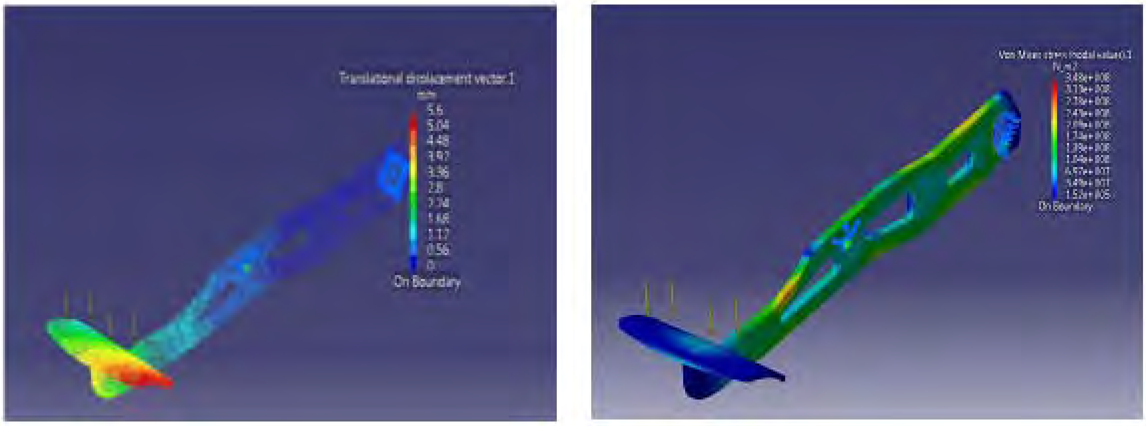


Fig. 3 Optimized shape of brake pedal after interpretation

IV. VALIDATION

To validate the structural integrity of the newly designed brake pedal, a finite element analysis was performed as to ensure that the design did not have any inherent stress concentrations or fatal flaws. The boundary conditions, load case and mesh parameters were the same as used in the optimization analysis. Figure 4 depicts the Von-Misses Stress distribution and displacement plot for the optimized design. Note that the stresses are fairly homogenous within the structure. This is precisely the goal of the topology optimization, and is the result of the algorithm which mimics the growth behaviour of biological load carriers like trees and bones, where the structures always tend to grow into shapes that have homogeneous surface stress [12]. From the finite element results of Figure 4, there does not appear to be any severe stress concentrations that would indicate a faulty design as the highest stress levels is 348 MPa meanwhile the material Tensile Strength is 550 MPa, that give safety factor roughly 1.6. In addition, the percentage of weight reduction is approximately 22 %.



(a) (b)

Fig 4. Displacement and Von Misses Stress distribution for optimized design

TABLE 1
Result before and after optimization

	Mass (kg)	Maximum Deflection (mm)	Von Misses Stress (MPa)	Factor safety
Initial design	0.74	3.9	289	1.9
Optimized design	0.58	5.6	348	1.6

V. CONCLUSIONS

The aims and scope of the research is to reduce the weight of an existing brake pedal design of a car with the application of topology optimization without the substitution of material. By determining the design constraints, load and boundary condition the topology optimization was run and the analysis converged after 45 iterations. However the result of optimization process needs for further refinement as it has manufacturability deficiency. Thus knowledge of design engineers to interpret and refine the proposed design is vital to ensure it is possible for production. In conclusion, the application of topology optimization with the integration of engineering knowledge of design engineer able to produce an optimal brake pedal design in a short time.

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REFERENCES

[1] Ashley, S. (2010) Shedding pounds on a magnesium diet. Automotive Engineering International, pp. 34-36.

[2] Yildiz, A. R., Kaya, N., Ozturk, F., & Alankus, O. (2004). Optimal design of vehicle components using topology design and optimisation. International Journal of Vehicle Design, Vol.34 (4), pp387-398.

[3] Cavazzuti, M., Baldini, A., Bertocchi, E., Costi, D., Torricelli, E., & Moruzzi, P. (2011a). High performance automotive chassis design: a topology optimization based approach. Structural and Multidisciplinary Optimization, Vol.44 (1), pp45-56.

[4] Kaya, N., Karen, İ., & Öztürk, F. (2010). Re-design of a failed clutch fork using topology and shape optimization by the response surface method. Materials & Design, 31(6), 3008-3014.

[5] Wang, Y., Zhu, G.N., Sun, B.Y. (2011) Topology Optimization in the Conceptual Design: Take the Frame of a Bender as Example, Advanced Materials Research, Vol. 267, pp297-301.

[6] Chang, J.W. and Lee, Y.S. (2008) Topology optimization of compressor bracket, Journal of Mechanical Science and Technology, Vol. 22, pp1668-1676.

[7] Yang, R. J., & Chahande, A. I. (1995). Automotive applications of topology optimization. Structural optimization, Vol.9 (3-4), pp245-249.

[8] Cavazzuti, M., Costi, D., Baldini, A., & Moruzzi, P. (2011b). Automotive chassis topology optimization: a comparison between spider and coupé designs. In Proceedings of the World Congress on Engineering 2011, Vol III WCE 2011, July 6 - 8, London, U.K.

[9] Costi, D., Torricelli, E., Splendi, L., & Pettazzoni, M. (2011). Optimization Methodology for an Automotive Hood Substructure (Inner Panel). Proceedings of the World Congress on Engineering 2011 Vo. III WCE 2011, July 6 - 8, London, U.K.

[10] Boonpan, A., & Bureerat, S. (2012). Multi–stage design of an automotive component. International Journal of Vehicle Design, Vol.60 (1), pp84-99.

[11] Salit, S.M. Molla, M.S.A. and Liakot Ali, M.L. (2005) Conceptual design of an automotive composite brake pedal. Suranaree J. Sci. Technol. Vol.12 (3). pp173-177.

[12] Harzheim, L. and Graf, G. (1995) Optimization of engineering components with the SKO method. SAE technical paper series, 951104.