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A Study About Shape and Topology Optimizations on A Connecting Rod

Erol Gültekin[1*], Mehmet Yahşi[2]

0000-0001-6114-7362 [1], 0000-0001-6665-0944[2]

[1] *Mechanical Engineering Department, Faculty of Engineering, University of Turkish Aeronautical Engineering, Ankara, 06790, Turkey*
[2]*Mechanical Engineering Department, Faculty of Engineering, Bursa Uludağ University, Bursa, 16059, Turkey*

Abstract

Internal combustion engines have progressed since they undertook a crucial role to convert chemical energy of fuel to mechanical energy with the reciprocating motion of the piston. Structural elements performed a role under heavy conditions with their facing dynamic stresses especially on the connecting rod with compression and tensile stresses. To overcome these stresses, manufacturing methods and design of the connecting rod have studied by the engineers for the different size and types of the engines so far. Many software are interested in structural optimization due to the demand of the field and present means on the application of finite element methods. Instead of focusing on kinetics of the connecting rod, this study, first, introduces design steps and optimization methods. Then, limitations were determined for a connecting rod, which had critical importance in a novel rhombic drive internal combustion engine (ICE). Shape and topology optimizations were used for the ICE part to reduce mass while keeping endurance limit of the structure. In the analyses, Hypermesh, Optistruct and HyperView tools of the HyperWorks were used. 50% mass reduction as a constraint was accomplished while the critical compression stress was increased only 26%, which was under the demanded limit of 320 MPa in topology optimization. In the shape optimization, maximum stress was increased to 304 MPa from 191 MPa while 20% mass reduction obtained. The results were compared with the former data.

Keywords: Connecting rod; Lever arm; Link; Shape optimization; Topology optimization

Research Article

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* Corresponding author

Erol Gültekin

egultekin@thk.edu.tr

Address: Mechanical Engineering Department, Faculty of Engineering, University of Turkish Aeronautical Association, Ankara, Turkey

Tel:+903125896108

1. Introduction

Internal combustion engine (ICE) is one of the important invent to be used on mobility of human and goods on the vehicles while supporting the countries on industrialization [1]. Many engineers and scientist study over a wide variety of ICEs from the point of construction, working fluid and operating cycles to develop their effectiveness for conversion of chemical energy to mechanical energy. Reciprocating motion of a piston inside the cylinder broadly accepted to carry out this duty due to its simplicity and a well performance especially on high speeds although having drawbacks on containing moving parts especially complex geometry with high manufacturing cost of crankshaft. On the other hand, connecting rod has also a vital role between piston and crankshaft to convert linear motion of piston due to gas pressure to rotation motion of crankshaft with its oscillating motion, which exerts oscillating forces on the cylinder walls via the piston thrust surface [2]. The section of the slider-crank mechanism is shown on the Figure 1. Connecting rods are under the effect of gas pressure, inertia forces and friction forces in dynamic conditions [3] and so, along the vertical axis, between the big end and small end, bending takes place, while on the horizontal axis compression stress and tension stress occur according to compression-power and intake of the engine, respectively [4]. Therefore, the most variable loads in ICE appeared on the connecting rod because of the oscillating motion and many times, design and manufacturing methods of connecting rod studied. Furthermore, instead of spending time on too different design, analyzing and manufacturing steps, optimization processes greatly reduce project time to be on the market. All the steps could be modelled to measure the performance, which is also the optimization of problems with satisfying all constraints [5]. Different from the conventional design improvement, in the last decades, mathematical, structural, sizing, shape and topology optimization methods are used in the concurrent design process to reduce time and integrating design and manufacturing [6, 7].

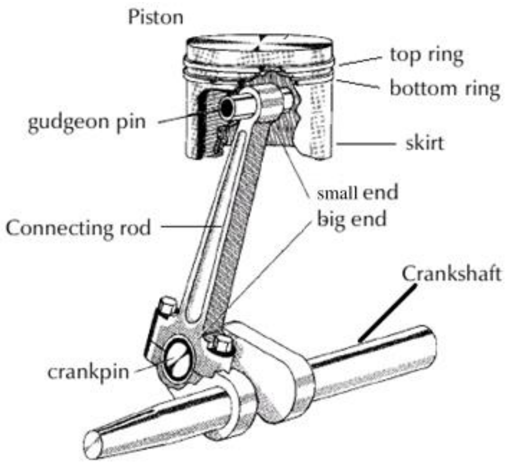


Fig. 1. Section of the slider-crank mechanism [8]

Lingaraj et al. [9] selected two wheeler connecting rod to optimize the shape and size according to static compressive load. They used maximum stress as a constraint and obtaining lighter mass as an objective on the design variable. The writers applied size optimization to reduce thickness of the web. Mishra et al. [10] modelled a motorcycle engine connecting rod with static loading and used topology optimization to reduce mass. They observed the maximum stress occurred near the oil hole at the small end of the connecting rod. They obtained 9.79% mass reduction with respect to former design. Roy et al. [11] studied on various model of connecting rod with fixing the ends for boundary condition and analyzed the static and fatigue loading results.

Kaya [3] studied on the linear static forces of connecting rod that exposes according to angular position of the crankshaft in three different size finite element model and changed the solid model to reduce weight. The writer analyzed each model to find optimized size and geometry. Shanmugasundar et al. [12] performed topology optimization on a connecting rod model and compared the data with the former one. They achieved 12.4%, 31.5 mm and 1.1% reduction on maximum principle stress, deformation and mass, respectively. Optimization could be applied different design problems such that Madrane et al. [13] studied shape optimization on computational fluid problem for inclined holes on the heat bearing in gas turbine. They measured the film-cooling performance with maximization numerically gradient-based method. Dong et al. [14] conducted shape optimization to fabric rubber seal, which are used on aircraft door seal to find optimal thickness. They concluded the results from the point of structural analysis considering gas pressure differences and temperatures on the cross section shapes of the seal as constraint and algorithm of optimization.

This study scope is introducing the fundamental optimization methods and performing shape and topology optimization to a connecting rod of a rhombic drive internal combustion to minimize the mass with keeping endurance limit of the machine element and comparing the data with the former design with the usage of Hyperworks.

2. Types of the Optimization

A series of trial constructs the design, which is directly related with the designer's experience, intuition, ingenuity and some mathematical analysis. An iterative method is used until obtaining an acceptable design. Therefore, for the engineers creating systems without compromising the integrity is a challenge while keeping design efficient and cost-effective conditions such as on material, energy, labor, etc. At this stage, optimization, which is a work to find minimum and maximum points of the function, will help the engineers [5, 15]. Conventional and optimum design processes are given in Figure 2a and 2b, respectively.

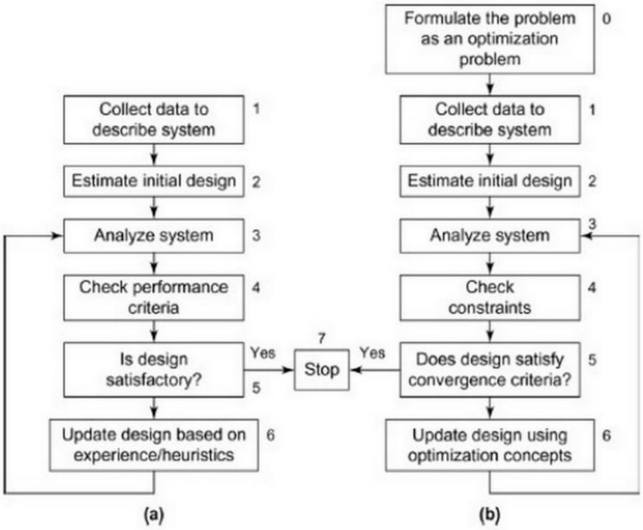


Fig. 2. (a) Conventional design process (b) Optimum design process [5]

2.1 Mathematical Optimization

The general optimization problem is formulated mathematically as minimization of the cost function subjects to constraints. This is called constrained optimization problem and could be founded as Eq (1) and (2):

$$x = \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{pmatrix} \tag{1}$$

where x is the vector of design parameters and minimizes the cost function, f(x).

$$\begin{Bmatrix} gi(x) \leq 0, i = 1, 2, ...m \\ hj(x) = 0, \ j = 1, 2, ...m \end{Bmatrix} \tag{2}$$

$g_i(x)$ and $h_j(x)$ are the inequality constraint function and the equality constraint function, respectively.

2.2 Structural optimization

This is the method to access optimal material distribution with respect to some common functions to minimize mass, displacement or the compliance especially using an iterative-intuitive process under the effect of designer's experience. Trial and error correct the iteration to find the demanded design and causing long time consumption while could result with suboptimal design. Structural optimization could be examined as size, shape and topology optimizations [6].

2.2.1 Sizing optimization

Size of the structural elements is used as design variable while the shape is known and the objective is optimizing of the structure with changing the size. That is the basic case of the structural optimization such as determining the diameter of a can when the required volume considered.

2.2.2 Shape optimization

Different from the size optimization, which determine the variable such as number of holes, or reinforcement, etc. the shape optimization focus on how the material distributes over the structure. With this method, diameter of the holes, radius of the fillets or rounds or any measures could be determined. Perturbation vector approach is used to be added linearly to vector of nodal coordinates (r_0) and shown in Eq (3):

$$r = r_0 + p \tag{3}$$

The design variables for the function taken is weights of the perturbation vectors. For each shape vector, one design variable could be rewritten as:

$$r = r_0 + \sum_{i=1}^{n} w_i p_i$$ where n is number of shapes/design variables and w is limits of weight $w_i^{\min} \le w_i \le w_i^{\max}$ i=1,…n.

2.2.3 Topology optimization

In this method, target is same as previous methods to find the optimal material distribution but on that case, resulting shape or number of holes etc. is not known. Density and homogenization provides the microstructure material distribution varying between 0% and 100% [6, 16].

3. Methodology

3.1 Design of the connecting rod

The rhombic drive single cylinder gasoline engine, which has a volume of 57.98 cc, stroke is 35.2 mm, and piston diameter is 43.213 mm. The connecting rod was designed with respect to the required parameter of the engine and the distance between the end centers is 47.84 mm. The geometry of the connecting rod is shown in Figure 3.

Fig. 3. (a) Connecting rod 3D model (b) manufactured component

According to emerged forces, to keep the endurance limit of the connecting rod material was selected 2379 alloy steel and physical and mechanical properties are given in Table 1.

Table 1. 2379 alloy tool steel physical and mechanical properties [17, 18].

Density	7.7x103 kg/m3
Melting Point	1421°C
Thermal Expansion	10.4 x 10-6 ºC
Poisson's Ratio	0.27-0.30
Elastic Modulus	190-210 GPa
Tensile Strength, Ultimate	965-1030 MPa
Tensile Strength, Yield	827-862 MPa
Compressive Strength	862 MPa

3.2 FE model and boundary conditions

Finite element model was built in Hypermesh software as shown in Figure 4. 1st order tetrahedral elements which have 1 mm average size were used. Total number of elements is 65613 and total number of nodes is 15938. Joints were modelled rigid spider elements in order to provide load transfer. All loads are coming from Multibody dynamics analysis and the maximum force values were used in linear static analysis [19]. For the solution method, inertia relief analysis was chosen because all joints are carrying loads from moving parts. With this way, inertia moment of the connecting rod inside the engine assembly evaluated individually through linear static condition. The connecting rod was subjected to loads as a moving part without fixing any ground platform. The force coming from piston connection was 7200 N and forces on rhombic links were 4237 N for each end.

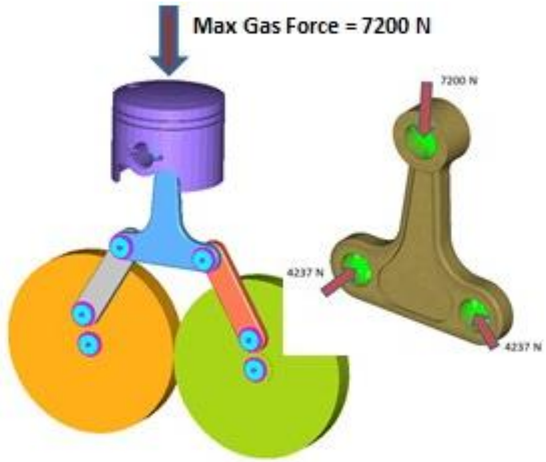


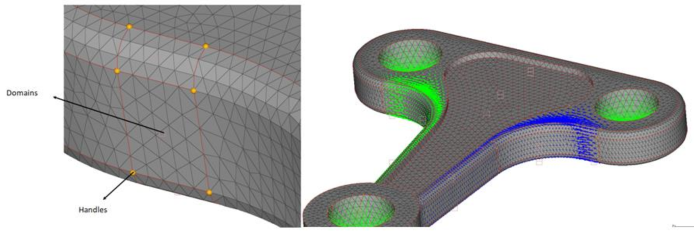
Fig. 4. Finite element model of the connecting rod

3.3 Topology optimization

Topology optimization method is a kind of structural optimization in order to achieve a proper concept design. As in all of the optimization methods, it is required to define design variables, constraints and objective of the optimization problem. In topology optimization, fundamental design variables are element densities. The finite element model, which was prepared for linear static analysis, was also used in optimization study. Firstly, it was required to specify design regions. Other areas were defined as non-design. Then, design variables were assigned to design regions. The design variables are element densities, which have a value between 0 and 1. At the end of the topology optimization, it was obtained an element density distribution. The concept design can be clarified by eliminating the elements under the threshold density value, which is specified to get proper structure. Constraints define a border of design variables by limiting outputs. For this study, the constraint was keeping 50% of volume fraction. Objective was aimed to minimize the compliance as a chosen output value.

3.4 Shape optimization

Shape optimization is also kind of a structural optimization, which is used to perform fine tuning studies. This method is used when the main geometry is certain and it allows to make changes on geometrical features such as holes, radii etc. In Hypermesh and many other preprocessors, it is possible to make small changes on features without remeshing the part and it is called as mesh morphing. Mesh morphing applications has done via assistant entities called “domains” and “handles”. Domains and handles can be considered as elements and nodes, respectively, and they are used to make changes in mesh model. All of these changes can be defined as “shapes” and they are used to define design variables. Design variables are numerical parameters, which have lower and upper limits of the shapes. During shape generation in Hypermesh, domains and handles are utilized to make feature changes, which are shown in Figure 5a and 5b. The constraints of the shape optimization problem was maximum von mises value, which coincide with 320 MPa as the endurance limit of the connecting rod. The objective was determined for the analysis minimizing the mass as soon as possible.



(a) (b)

Fig. 5. (a) Domains and handles (b) Shapes

4. Results

4.1Topology optimization

At the beginning of the topology optimization, design and non-design zones were defined. Prepared topology optimization model is shown in Figure 6. Blue zones are non-design areas including first layer of the elements touching rigid spiders. These elements were excluded in order to provide structural integrity. Yellow zone is design area.

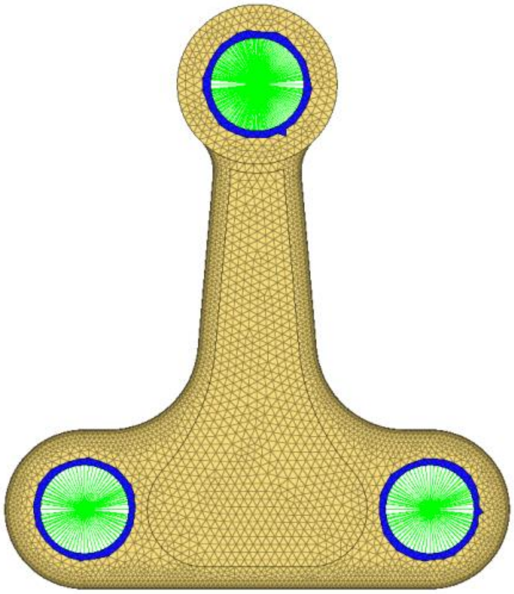


Fig. 6. Topology optimization model.

After 16 iterations, final structure of the model, which has minimum compliance regarding 50% lighter than initial mass, was achieved. The topology result is shown in Figure 7.

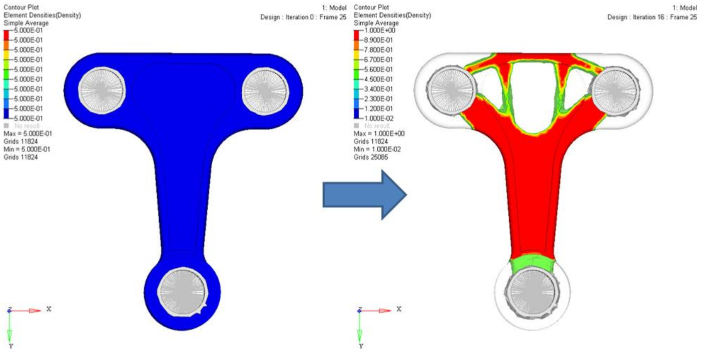


Fig. 7. The topology optimization results

It can be said that strength of the part is still acceptable. Initial model has maximum 191 MPa von mises stress under the load conditions and this value became 240 MPa after topology optimization. The maximum von mises stress is still under the endurance limit of the material, which is 320 MPa. After the topology optimization, the maximum stress shown in Figure 8.

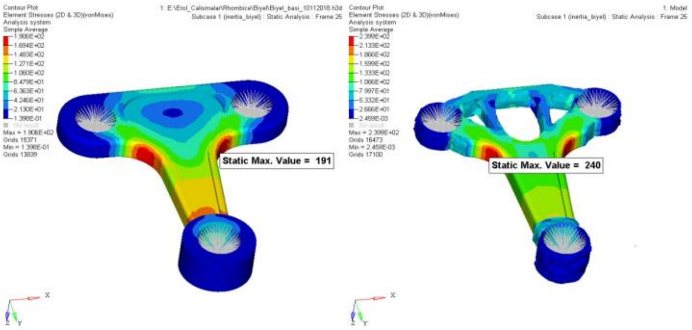


Fig. 8. Comparison of stress results for initial and topologically optimized models

4.2 Shape optimization

Another structural optimization method, which studied in this model was shape optimization. In this study, the shapes were defined on the model as in Figure 9. Shape 1 is the thickness of the middle zone of the part, shape 2 and 3 are the radii.

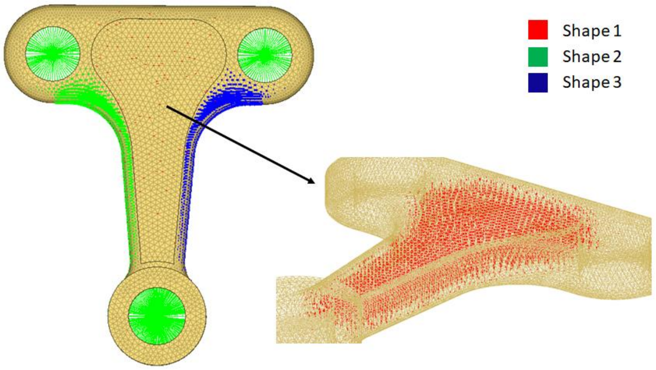


Fig. 9. Shape definitions on connecting rod model.

Optimization algorithm make changes on these shapes in order to obtain optimum results under certain constraints. After the optimization, shape 2 and shape 3 design variables remained as constant and equal to zero, and shape 1 became approximately 0.9 as shown in Table 2.

Table 2. Shape changes at the end of the optimization

```
--------------------------------------------------------
  Design    Design    Lower       Design      Upper
 Variable  Variable   Bound      Variable     Bound
    ID       Label
--------------------------------------------------------
        1  desvar1   0.000E+00   9.185E-01   1.200E+00
        2  desvar2   0.000E+00   0.000E+00   1.200E+00
        3  desvar3   0.000E+00   0.000E+00   1.200E+00
--------------------------------------------------------
```

After shape change application, thickness of the middle zone of the part was reduced to 1.3 mm from 4 mm. Therefore, mass was reduced to 48 gr from 60 gr. Approximately, 20% weight reduction was achieved at the end of this study. Strength was also acceptable without violating the constraint during optimization. Stress results is shown in Figure 10.

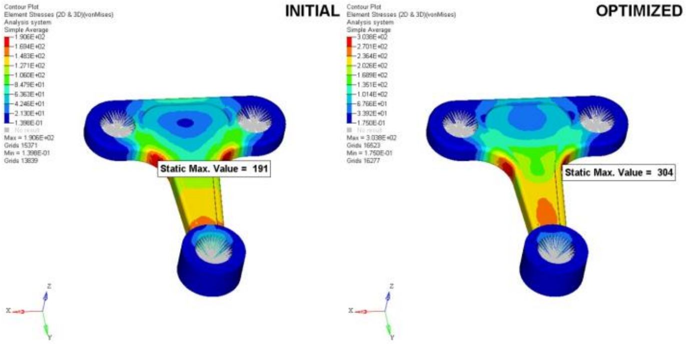


Fig. 10. Stress results comparison of initial and optimized models

5. Concluding

In this study, fundamental optimization methods were introduced. Shape and topology optimization were considered as an alternative solution of the problem and applied to a connecting rod of a rhombic drive internal combustion engine. After the optimization, maximum stresses were evaluated with finite element model analysis and compared with the former model. Mass reduction gain according to stress increase in the topology optimization was greater than the shape optimization.

As a further study, the structure obtained from the topology optimization could be modelled with CAD, and then, application of shape optimization could be used more efficiently to reduce the mass more. On the other hand, the models obtained with topology optimization are generally evaluated for the conventional manufacturing methods and that could cause deviation from the structure. To overcome loss in gain of final design, additive manufacturing could be used to produce the component directly with the demanded structure.

Nomenclature

CAD	Computer Aided Design
ICE	Internal combustion engine
x	Vector of design parameter
g_i	Inequality constraint function
h_j	Equality constraint function
n	Number of shapes/design variables
p	Perturbation
r	Design variable
r_0	Vector of nodal coordinate
w_i	Shape weight

Conflict of Interest Statement

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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