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Design Optimization of the control arms of a Double Wishbone Suspension System using Topological Approach

Aditya Singh[1], Soham Pawar[2], Manish Soundalkar[3] , Dr. Mohammed Anwar Ali[4]

[1]*Department of Automobile Engineering, Theem College of Engineering, Boisar*
[2]*Department of Automobile Engineering, Theem College of Engineering, Boisar*
[3]*Department of Automobile Engineering, Theem College of Engineering, Boisar*
[4]*Department of Automobile Engineering, Theem College of Engineering, Boisar*

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Abstract - This paper focuses on design optimization of an existing double wishbone type suspension system from a consumer vehicle. The suspension system acts as a key element in between the vehicle and the road, and has a significant impact on the handling and feel of the vehicle. The suspension system is a critical system that directly influences vehicle dynamics, ride comfort and overall driving experience. Optimizing core suspension factors such as weight, strength and geometry are a key to achieving optimal performance, handling, ride quality and stability. Known for its precise handling characteristics and superior ride comfort, the double wishbone suspension is an ideal candidate for improving its design to a new ceiling. By using FEM with the principles of topology optimization, we aim to create an optimized control arm design that is lighter in weight as compared to its original design, without significantly affecting its strength characteristics.

Key Words: control arms, double wishbone suspension, topology optimization, design, efficiency, lightweight design.

1. INTRODUCTION

The suspension system plays a pivotal role in connecting the passenger to the road. It largely determines the handling, ride quality and passenger comfort, which makes the suspension system a key element to be optimized in order to improve the performance characteristics of a vehicle. Its design must strike a delicate balance between factors such as weight, strength and geometry in order to ensure optimal handling, stability and safety. In this pursuit of optimizing design, Topology optimization is an effective tool that can be used to enhance the efficiency of the existing design of the suspension control arms.

This paper aims to improve upon the existing design of the control arms of a popular Indian SUV. Reducing the mass of the control arms will result in reduction in the overall un-sprung mass of the vehicle, which can improve handling of the vehicle. Since the proposed design will use less material as compared to the original, there will be a reduction in the overall material costs.

2. LITERATURE STUDY

Swapnil S. Khode et. al.[1] have conducted a study on design optimization of the lower control arm of an LCV. The optimization process reduced weight of the lower control arm used in a MacPherson Strut type suspension by 17.5%. The weight reduction was achieved while keeping a factor of safety that ensures that the stresses and strains are within the permissible limit.

Liang Tang et. al.[2] have established a topology optimization model for a control arm which considers the influence of ball joints and bushings on the control arms. The study focuses on several load cases[3], based on which a control arm design is obtained using the topology optimization results. The strength of the newly designed control arm is compared to the original design.

Aaditya Chandrasekhar et. al.[4] have developed methods to simultaneously optimize the material as well as the geometry. The paper proposes the use of Variational Auto-encoders (VAE) for simultaneous optimization. The use of VAE consists of a material database and an FEM solver. Several papers that focus on designing a double wishbone suspension [5]–[8] were studied, the main aim of the authors were to create a design that is high strength as well as cost effective.

After conducting a literature study, it was found that most of the research regarding design optimization process of the suspension system focused on creating a new design. However, these methods yield a design that cannot be manufactured using conventional methods which will result in high production cost. This paper focuses on creating an optimized design that can be manufactured using conventional methods.

3. METHODOLOGY

The design optimization and validation process requires the following steps:

1. <u>Data Gathering:</u> This process involves the study of the suspension system and its components. The dimensions of all suspension components are measured using vernier calipers, measuring tape and other measuring instruments.

2. CAD modeling and assembly: The data gathered from the previous step is used to create a CAD model of each component. The components include upper and lower control arms, steering knuckle and upper/lower ball joint assemblies.
3. Material Selection: Aluminum Alloy (AA 6061 T6) is selected for both the control arms due to its high strength and lightweight characteristics. The initial mass of the upper control arm was found to be 1.268 kg and that of the lower arm was found to be 6.128 kg
4. Preliminary analysis: The preliminary analysis consists of applying several loading conditions on the control arm assembly. Using multiple loading conditions will give a better understanding of the performance of the control arms.
5. Topology Optimization: The solutions from the preliminary analysis are used to setup the optimization block. A new control arm design is obtained through this process. Density based method is used to perform the topology optimization.
6. Design Validation: The new design is subjected to the same loading conditions as the original design. The differences in peak stress, factor if safety and fatigue are compared.

4. PRELIMINARY ANALYSIS

4.1 Pre-processing

Since the analysis type is "Static Structural" the contact definition in between all mating parts is set to "Bonded" to create a rigid assembly. The study focuses on the control arms, hence the control arms are meshed using a finer quality mesh. The mesh size for the control arms ranges from 3mm to 14mm for different faces. The mesh statistics are given in the table below:

Statistics	
Nodes	118188
Elements	65255

Fig - 1: Mesh Statistics

The element quality metrics are shown in the graph below:

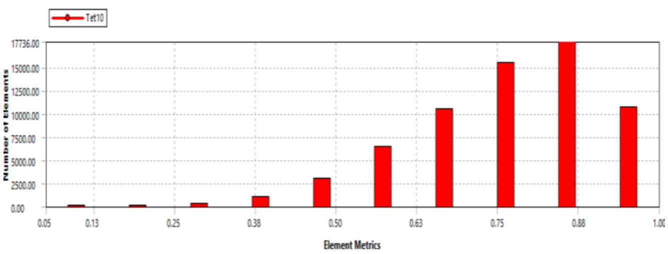

Fig - 2: Mesh Quality Graph

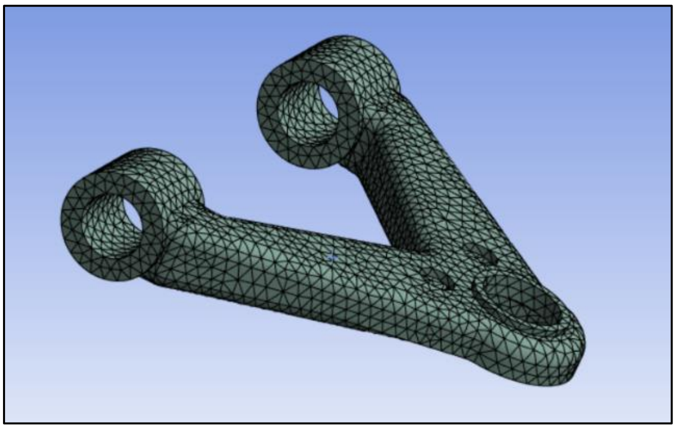

Fig - 3: Upper control arm mesh model

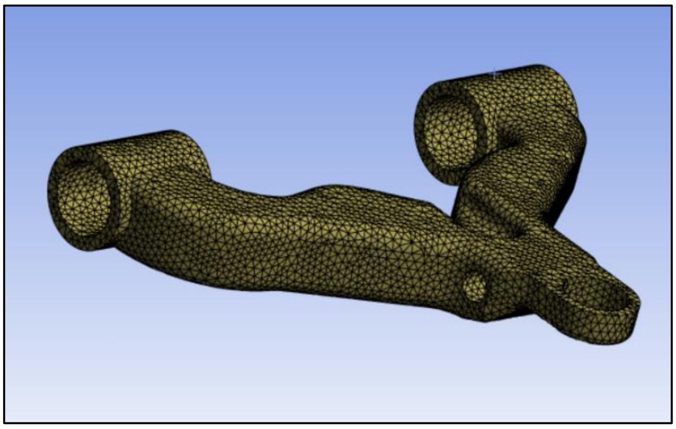

Fig - 4: Lower control arm mesh model

4.2 Loading conditions

The first selected loading condition is based on the vehicle being under maximum load in a stationary condition, including the weight of the fuel, passengers and luggage.

Vehicle kerb weight = 1755 kg

Passenger weight = 65 kg

Number of passengers = 4

Fuel tank capacity = 57 L

Therefore, maximum fuel mass = 42 kg

Luggage = 50 kg

Gross vehicle weight = Kerb weight + Passenger weight*4 + Fuel mass + luggage = 2107 kg

Assuming equal weight distribution, The load acting on each wheel = (2107/4)*9.81 = 5167.5 N

Forces in the other loading conditions are sourced from previously studied literature[3]. The force components are shown in the table below.

Sr. No.	Load Case	Fx (N)	Fy (N)	Fz (N)
1.	Max. load under stationary condition		5167.5	
2.	Driving along a curved road	-	-8197.3	8118.8
3.	Sudden Braking	6900.6	-	6390.7
4.	Kerb Strike	-	-30008.3	4491.4

Table - 1: Different load cases

- Cylindrical supports are applied on points where the control arms connect to the chassis as well as the connection point on the lower arm to the shock absorber.
- The load is applied through the steering knuckle as shown in the figure below.

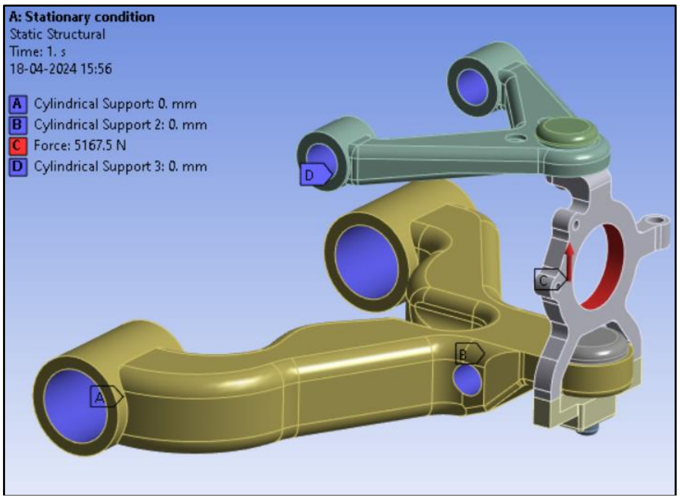

Fig - 5: Preliminary analysis setup

5. TOPOLOGY OPTIMIZATION

The results obtained from the previous section are used to setup the topology optimization. Mass response constraint is used to define material retention, the goal is to retain 50-90% of the material by mass.

Definition	
Type	Response Constraint
Response	Mass
Define By	Range
Percent to Retain (Min)	50 %
Percent to Retain (Max)	90 %
Suppressed	No

Fig - 6: Response constraint

The exclusion region is selected based on the results from the previous section, regions of high stress concentration are excluded from the optimization region in order to maintain strength. "Density based" type of Topology optimization method is used.

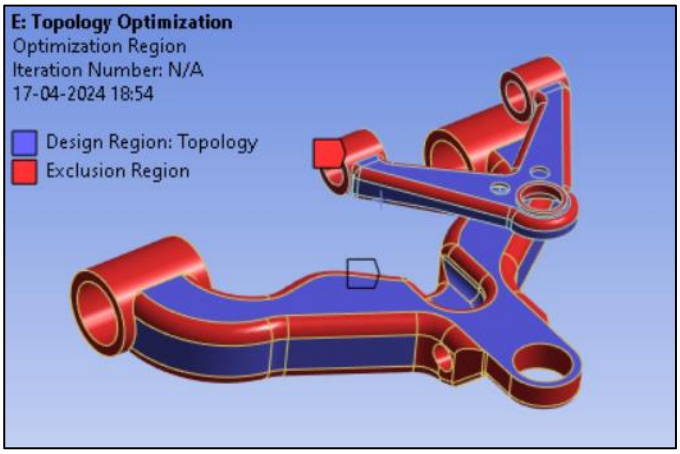

Fig - 7: Exclusion region setup

The topology optimization results show a 13.41% reduction (approx. 1 kg) in combined mass of both the control arms.

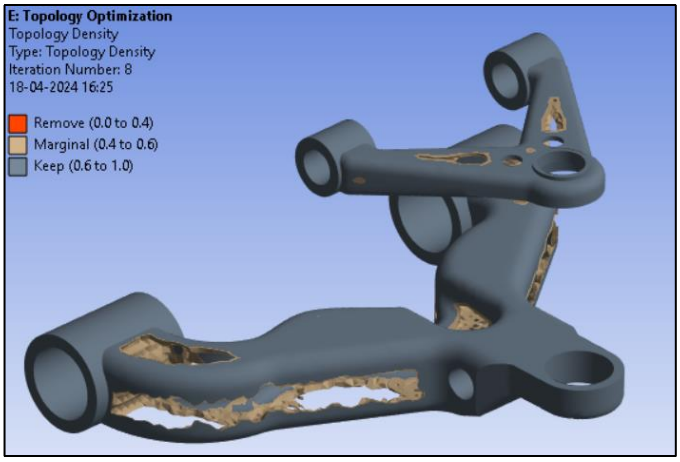

Fig – 8(a): Optimized Design

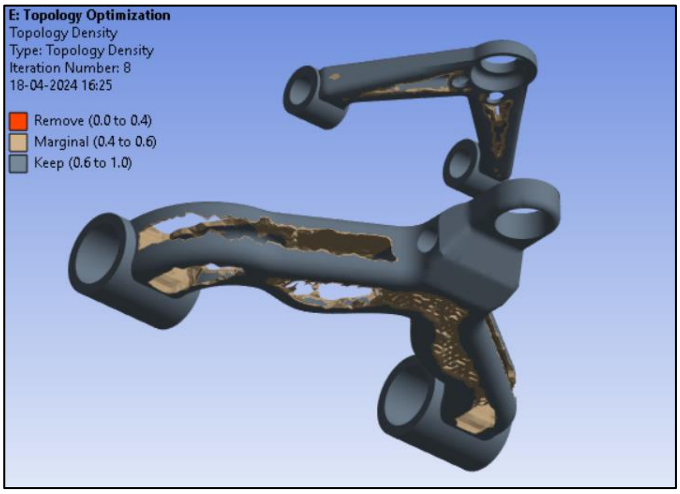

Fig – 8(b): Optimized design

Original Mass	7.3995 kg
Final Mass	6.4072 kg
Percent Mass of Original	86.59

Fig - 9: Original vs Optimized mass

As seen in Fig - 8(a) and Fig – 8(b), the optimized design has several irregularities and cannot be directly used for validating the design. A new design based on the topology optimization results is created.

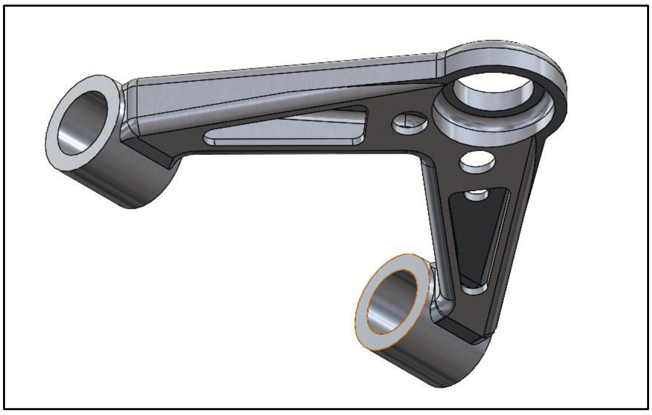

Fig - 10(a): Optimized upper control arm

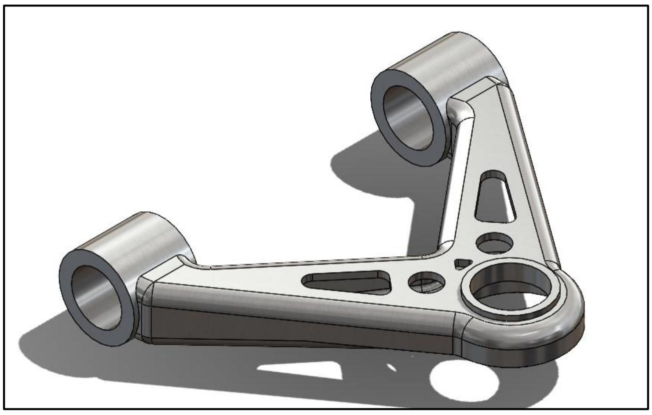

Fig - 10(b): Optimized upper control arm

- Upper control arm original mass: 1.268 kg
- Mass after optimization: 1.091 kg

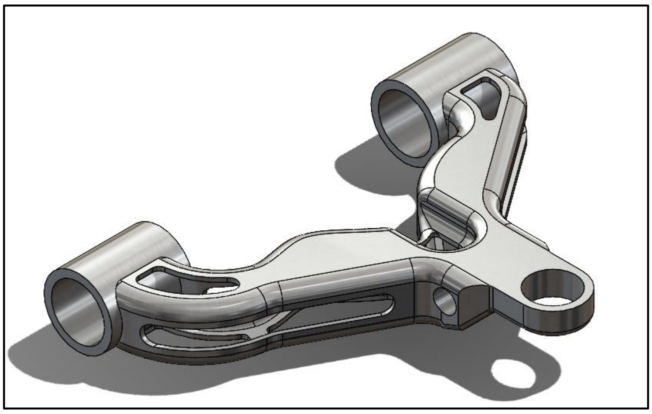

Fig - 11(a): Optimized lower control arm

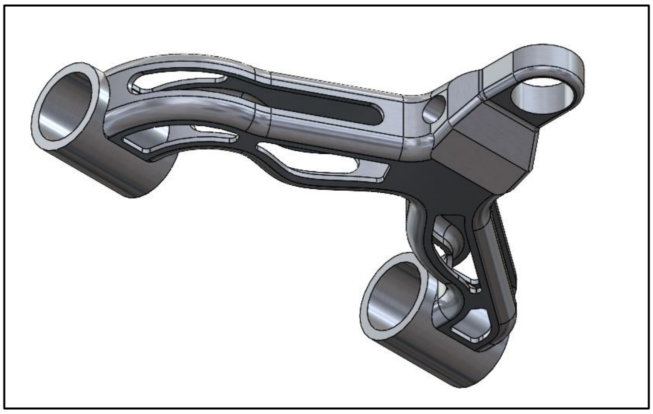

Fig - 11(b): Optimized lower control arm

- Lower control arm original mass: 6.128 kg
- Mass after optimization: 4.935 kg

6. DESIGN VALIDATION

The proposed design is subjected to same loading conditions as the original design. The results are compared across each condition and tabulated below.

Sr. No.	Load Case	Peak Stress Value (MPa)	
		Original Design	Proposed Design
1.	Fully loaded under stationary condition	42.473	52.419
2.	Driving along a curved road	133.13	146.36
3.	Sudden braking	109.14	118.74
4.	Kerb Strike	235.53	244.5

Table - 2: Peak Stress Comparison

Sr. No.	Load Case	Minimum Safety Factor	
		Original Design	Proposed Design
1.	Fully loaded under stationary condition	6.592	5.341
2.	Driving along a curved road	2.103	1.913
3.	Sudden braking	2.565	2.358
4.	Kerb Strike	1.188	1.058

Table - 3: Minimum Safety Factor Comparison

Sr. No.	Load Case	Minimum load cycles till Fatigue	
		Original Design	**Proposed Design**
1.	Fully loaded under stationary condition	1×10^8	1×10^8
2.	Driving along a curved road	1.03×10^6	5.22×10^5
3.	Sudden braking	5.99×10^6	2.21×10^6
4.	Kerb Strike	6882.4	4523.8

Table – 4: Minimum fatigue limit comparison

7. RESULTS

The combined mass of both control arms in the proposed design is 6.026 kg, which is an 18.53% reduction from the original mass. Results from tables 2,3 and 4 suggest a reduction in overall strength of the control arms, however the design is within safe limits in each load condition. The proposed design can be manufactured using conventional methods.

There is a reduction in the unsprung mass of the vehicle by 2.742 kg, which could marginally improve the handling of the vehicle. The vehicle model on which the original design of the control arms is based on sold 61,000 units in the year 2023. Considering cost of material to be 450 Rs/kg, the overall material cost would have reduced by 7.526 Cr. for the year.

8. CONCLUSION

A procedure for optimizing the design of the control arms of double wishbone suspension is described. The same procedure can be applied to other vehicle systems with some modifications to reduce weight. The proposed design achieves the objectives of reducing mass and material cost while being within permissible limits. The main contribution of this paper is the consideration of conventional manufacturing methods in the optimization process. The limitation of this paper is that the paper is based only on utilizing FEA software, experimental results may vary.

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