Design optimization of steering knuckle by adopting bionic design approach

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Abstract. Weight optimization plays vital role in performance improvement for an automobile. In vehicle, steering knuckle is one of critical components as it is subjected to millions of varying cyclic loads and it contributes to unsprung mass of vehicle. Therefore, steering knuckle of passenger vehicle is selected for this research work. The aim of this research work is to relate optimized shape of the part with bionic shape, which will give the optimum design. Topology optimization is used as a tool for getting optimum material layout with given space and boundary conditions. The objective function for topology optimization is to maximize stiffness with minimum mass constraints as 30%. The optimization is done by Altair INSPIRE software in which the part is imported as cad model with SG 500/7 as part material. The final surface modeling is done by Polyworks software package for parametric model and result of that modelling has been applied for the standard analysis of the part. The proposed design of the parts meets the strength and stiffness as per requirement. For physical prototype the part is manufactured by additive manufacturing using AlSi10Mg as a material and required properties for same material is also generated. New proposed design of the part shows that there is reduction in weight by 35%.

1. Introduction
Mass manufacturing techniques evolved over past few decades have ensured economics of scale. However limitations of these techniques have invariably forced part designs to be actually inefficient. With the progress into a highly competitive market place further getting constrained to environment/ecology conservation, light weighting has become a focus area in automobile industry. While light weighting can be achieved in principal through extensive use of polymers; polymers offer three challenges namely cost, durability and end of life scrap handling have not allowed deep penetration of polymers in functional areas of automotive vehicles.

Evolution of 3D printing in past three decades has been offering this feasibility of creating most efficient part designs that can be realised physically which was impossible by conventional process. Bionic shape designs which are inspired through shapes of plants and animals has become a standard thought process for mechanical parts shape optimization. Nature is the best way to study for optimum material layout with best possible shape, because it has material only where it is required. Steering Knuckle is one of the main components used in the steering system of automobile which contains wheel hub and connects it to suspension and steering components. It undergoes millions of varying
cyclic loading conditions which tends to fatigue failure of the part. Steering knuckle comes under unsprung mass so lighter the weight, greater the power saving and lesser the vibration (Less inertia). Topology optimization is the tool for the lightweight structure for the bionic design in a given design space [1]. Shape optimization is carried out by performing static analysis as base, which intended to fulfill the weight reduction objective. Shape optimization aim is to modifying the part boundaries with given constraints and improve the performance of the structure [2]. Because of geometric complexity of the part after optimization were hardly convertible into manufactural parts due to the conventional manufacturing’s inherent design restrictions. But Laser Additive Manufacturing is rising the grade of the design freedom and manufacturing possibilities [3]. Method for converting a optimize material layout into a STL file which is adaptive for additive manufacturing by using B-spline curve fitting as a tool [4]. V. Sivananth and S. Vijayarangan has done optimization of passenger car steering knuckle for the fatigue loading and he found that steering arm region is the critical part under the cyclic loading conditions. The failure region of the knuckle was optimized under operating load conditions and fatigue life increased [5]. Ti6Al4V alloy parts are widely used in this sector because of their good mechanical properties-to-weight ratio. For optimization Inspire software package is used as a tool. Further it is manufactured by direct metal laser sintering as an AM process [6].

2. Bionic design case study

Optimize structure inspire from nature are used as a basis to improve product design. an air suspension system was created using bionic approach to decrease the required air pressure and increase the suspension force. The bionic structure used for relating the air suspension system is albatross wings. Albatross wings have better flight mechanism that permits it to cooperate with complex environment. System consist of guide rail and a slider which is based on principle that the airflow is coming from the air outlet hole towards the guide rail. Using the bionic albatross wing’s surface structure, the guide rail surface was designed into diverse structures and concludes that air pressure in air static rail is reduced by 37% in standard working condition [7].

3. Optimization

3.1. Process flow

The primary thing for the optimization is to define the objective function. Here the objective function is to maximize the stiffness with minimum mass constraint as 30%. Then optimization space have to identified and accordingly the given space is divide into 2 parts mainly design space and non-design space. Design Space is the volume where the optimization process carried away from, creating the most efficient material distribution capable of withstand the forces applied to model and Non-Design Space is the region within the model in which material will not be removed. This area is still included in the simulation, but excluded from modification. The process flow for topology optimization is as shown in figure 1.

3.2. Load Estimation

The vehicle is run on the track for calculating the loads that are coming on the wheel which will then transfer to the steering knuckle and suspension system. For calculating the load Wheel Force Transducer is used which will give the six components as forces and torques in X, Y and Z directions on the rotating wheel. Data output referred to vehicle coordinate system. The forces are calculated is in the form of G force that is acceleration force. This loading data will be the input condition for the analysis of the part which further will give optimize material layout. Force data is collected in X, Y and Z directions at contact patches and wheel center.

3.3. Material

The material used for manufacturing the steering knuckle is SG 500/7 iron, the properties for the same is as shown in table1. Conventionally the steering knuckle is manufactured by sand casting process. The aim of this paper is to optimize the part with given material without giving any manufacturing constrain to obtain the optimum material layout.
Table 1. Material properties for SG 500/7.

| Property                | Value  |
|-------------------------|--------|
| Density (gm/cm³)        | 7.1    |
| Yield strength (MPa)    | 320    |
| Ultimate Strength (MPa) | 500    |
| Young’s Modulus (GPa)   | 170    |

3.4. Load and Boundary conditions

The geometric model of steering knuckle is as shown in figure 2. The boundary conditions for optimization are as shown in figure 3. The lower ball joint and strut mounting points are constraints in all translation degree of freedom. The steering arm region is constraints in only y translation. The stiffness values for upper and lower caliper lug is also calculated based on unit load application along with the related displacement caused. Vehicle stability control is one of the major parameter for smooth operation of vehicle without any fatigue. For this toe and camber stiffness calculation becomes the primary concern and its value should be exceeding minimum permissible assessment. Toe and camber stiffness is determined by giving unit loading moment and analyzing the related displacement for stiffness calculation. This stiffness should match the particular standard for finalizing the part geometry.

3.5. Analysis

For Basic analysis of the part the boundary conditions and constraints are applied according to the loading cases. The von mises stress distribution plot for all loading conditions is as shown in figure 4. Four nod quadrilateral elements are considered for meshing. First the coarse meshing is done then in
every subsequent iteration the local meshing is done at the critical section where the stress concentration is observed. Only critical load cases have been selected, because other cases are not having any considerable influence on the steering knuckle. The bump and kerb strike cases are influenced most due to sudden impact on the tire which will then transfer to the steering knuckle. During steering arm fatigue analysis or rack cycle force analysis the tie rod region is subjected to the cyclic loading of stress amplitude 6000N with mean stress as zero. For this analysis the wheel hub portion is constrain in all degree of freedom and load is applied in the tie rod direction. This will give the strength analysis of the steering arm.

3.6. Material layout
The optimum material layout is obtained as per the load cases, constraints and boundary conditions and is as shown in figure 5. Strut part and wheel hub bearing region is the most stress zone with given load cases because stress at part crosses the yield strength but it is within the permissible range of plastic strain.

![Figure 4](image1.png)  ![Figure 5](image2.png)

Figure 4. Von mises stress plot for static analysis. Figure 5. Optimum material layout.

The area of higher stress will get identified and according to optimization the area of higher stress will have more material. The regions where less stresses are there the pockets are made accordingly.

3.7. Modeling
The optimum material layout is considered as a base for the final modeling of the part. The material layout given by the software for modeling is infeasible according to the practical approach (under working condition of part) because cross-section at some points are having very less thickness and support for load carrying. Those portions are shown in figure 6a with red circles. Therefore, modification is done at steering arm region and brake caliper region. For modification n number of iterations followed by the analysis of the part have been carried out with all the functional requirement of the part remains the same. The final geometry of steering knuckle is as shown in figure 6b. For validation, the optimized part is again analyzed by using Hyper mesh for mesh generation, Abaqus as a solver and hyper work for result verification.
Figure 6. a Modeling as per material layout by software, b Final optimize design, c Metal 3d printed steering knuckle with support structures.

4. Bionic Design
The bionic approach methodology is used for transforming material layout to final design for steering knuckle, where the material layout is relating to the mimic nature and animals’ anatomy. The calliper region is as shown in figure 6b (portion p) has relatatable structure as a triactyl bird feet anatomy. In birds this anatomy is for clamping and stiffness purpose. Same functional requirement for steering knuckle at the point of calliper side. The strut portion as shown in figure 6b (portion q) is structure similar to the horse anatomy. Nuchal ligament with the abdominal muscles will try to relieve the back muscle weight so that rider’s weight can be contentedly carried out. By studying and implementing this bionic geometry the load bearing capacity of the part will get increased. This implementation phase is never ending and iterative process.

5. Manufacturing
5.1. Material
Considering the manufacturing feasibility of the final design Additive manufacturing is the only approach for physical part. This part for actual automotive application needs to be made in SG 500/7 from cost perspective. However we carried out an experiment using AlSi10Mg. Since SG500/7 printing technology does not exist today. Over the past few years, the AM industry has been using several types of aluminium alloy powders. A wide range of aluminium AM parts have been developed for a variety of application using AlSi10Mg and today it is the most popular aluminium alloy powder grade in the metal AM industry. So AlSi10Mg has been selected for the metal 3D printing of steering knuckle. The composition of AlSi10Mg is as shown in table 2.

Table 2. Composition of AlSi10Mg.

| Aluminum (Al) | Copper (Cu) | Iron (Fe) | Magnesium (Mg) | Manganese (Mn) | Silicon (Si) | Titanium (Ti) | Zinc (Zn) |
|--------------|-------------|-----------|----------------|----------------|-------------|---------------|----------|
| balance      | ≤ 0.05      | ≤ 0.55    | 0.2 - 0.45     | ≤ 0.45         | 9.0 - 11.0   | ≤ 0.15        | ≤ 0.10   |

The properties of the 3D printed materials depend on several factors based on which its value changes accordingly. The factors are particle size, powder production method, printing orientation etc. Due to above concern the properties for the AlSi10Mg has been generated.

5.2. Tensile Test
The standard specimens for tensile test are 3D printed as shown in the figure 7. Specimen tension tested as per ASTM E384-11. Stress relieved at 300°C±10°C for 2hours and it is air cooled. The
tensile test results are as shown in table 3. AM material properties in Vertical and 45° are similar to 90% of the horizontal direction properties. AM material properties are in stress relieved condition and without any other heat treatment.

![Figure 7. Standard Metal 3D printed part for testing.](image)

**Table 3.** Tensile test result.

| Orientation  | Tensile strength (MPA) | Yield strength (MPA) | Average Elongation (%) |
|--------------|------------------------|----------------------|------------------------|
| Horizontal   | 385.33                 | 287.5                | 5.2                    |
| 45° Angle    | 353.33                 | 250                  | 3                      |
| Vertical     | 353.33                 | 275                  | 5                      |

The steering knuckle is 3D printed with Direct Metal Laser Sintering with AlSi10Mg as a printing material and is shown in figure 6c with support structures.

### 6. Conclusions

An overall idea about the material layout is identified by using topology optimization as a tool. This material layout is used for relating this shape to the bionic shapes and converts it to the solid model. The optimization process is accurate, quick and easy to implement. The quality of the product is matching the strength and stiffness criteria required for efficient functionality of the part. The bionic design weight optimization results in 35% reduction in weight. Additive manufacturing provides an option to print bionic shapes as per the actual design. In future we are exploring further same part by casting for production.

### 7. References

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