Design, analysis, and optimization of an FSAE upright

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Abstract. Components of a formula car experience many forces and have to sustain in various conditions. The design of the components must be keeping in mind the safety and efficiency of the component. In Formula racing, the car has to be as light as possible. Cars with powerful engines are faster in the straights, but cars with lighter weight are faster in the corners. Optimizing the components to be light in weight is a critical task and has to be done meticulously. Several conditions and forces have been considered, and the simulation has to be as close to the real-life conditions as possible for accurate results. This paper records the detailed study, design, and analysis done for the weight reduction of the component. Data from previous years' performance of the car was also considered during the analysis. Based on the data, the material selection and designing of the component was made in Solidworks. The Structural and Fatigue analysis were done in ANSYS Workbench; based on these results, the component's optimization was done.

1. Introduction
Formula Student is an engineering design competition which is held all over the world in different countries. It is the right platform for engineering students around the world to learn and showcase their engineering skills. Each year Formula Student teams design and build open-wheel, open-cockpit race cars and compete in these events worldwide.

The upright or knuckle is an essential part of the vehicle as it holds the wheel assembly together. The design and manufacturing of this part have to be up to the mark. The component faces many forces and loads. Some of the loads and forces cannot be predicted or calculated, like the impact of an unexpected bump. Being a Formula car, this runs on race tracks with very few undulations and bumps. Nevertheless, it has to be kept in mind that the car travel speed is very high and is subject to high g-forces.
2. Methodology

2.1. Iterative design process:
An iterative design process is followed for the optimization of the upright design. As this paper’s focus is away from generative design, the iterative design process is a good alternative to optimize the design of any mechanical component. The overview of the process is explained in the flowchart, as shown in figure 1.

![Iterative design process](Image)

**Figure 1.** Iterative design process

The above procedure has yielded promising results, and when executed by using basic principles and the proper engineering practices, it will lead to an optimized and improved design. Whenever there is a lack of access to generative design and subsequent 3D printing, metal 3D printing, this method can very well be used to optimize the design.

2.2. Data acquisition
A significant part of the design process is based on the data collected during the competition the previous year. Data was collected in dynamic events like Autocross and Endurance Race. This data
was processed and studied, and the inferences from this were taken as input parameters for the design. Vehicle speed, g-forces experienced, and the path on the track was some parameters that were derived from the acquired data as shown in table 1. Load calculations were done considering the car’s g-forces, which we derived from the data acquired.

| Table 1. Data acquisition of the car’s performance on the track. |
|---------------------------------------------------------------|
| **Autocross** | **Endurance** |
| Max. Speed Achieved (Km/Hr) | 67 | 129 |
| Average G Force Experienced (G) | 2.3 | 2.7 |

2.3. **Analytical calculations**

The following parameters offer significant loads and conditions on an upright. Upright affects the vehicle dynamics greatly, and all these parameters are calculated based on vehicle dynamics of the car and upright under study [1][2].

2.3.1 **Braking force:** Force on front callipers = Braking torque / Radius of rotor

= \( \frac{T_{br}}{R} \)

= \( \frac{383.73 \times 10^3}{62.5} \)

= 6124.98 N

2.3.2 **Steering force:** Reaction at each tire = \( \frac{R_A}{2} \) + (6 × 9.81)

= \( \frac{1617}{2} + 58.86 \)

= 867.36 N

Therefore, force applied by tie-rod = 0.7 × 867.36

= 607.15 N

2.3.3 **Cornering force:** % of load transfer, LLT = \( \frac{g \times \text{height of CG}}{\text{Track Width}} \)

= \( \frac{2.7 \times 0.254}{1.219} \)

= 0.31%

% load on inner wheels = 0.5 – 0.31 = 0.19 = 19%

% load on outer wheels = 0.5 + 0.31 = 0.81 = 81%

Load transferred on outer wheels = (81/100) × 270 = 219.38 kg

Load transferred on front outer wheel = (219.38 / 2) = 109.6 kg

= 1096 N

2.3.4 **Lateral Force:** \( F_l = g \times 9.81 \times \text{mass on single wheel} \)

= 2.7 × 9.81 × 75

= 1986.525 N

2.3.5 **Vertical Load:** \( F_v = \text{Mass on wheel} \times 9.81 \)

= 75 × 9.81

= 735.75 N
3. 3D Model

3.1. Geometry

The 3D Modelling was done in Solidworks 2020. As the design philosophy was to mainly optimize the upright from the 2019 vehicle, the design was started with the 2019 model as the base geometry. A fundamental structure was designed, and then based on the boundary conditions and mounting points on the upright, optimization was carried out. The 2019 upright was for a 13-inch wheel. The new 2020 design is for the 10-inch wheel.

48.61% reduction in weight was achieved in the new design compared to the old design of the upright. FEM analysis of the upright was done to justify the safety of weight reduction. The old and new designs of the upright and its mass properties are shown in figure 2 and figure 3.

![Figure 2](image1.png)

**Figure 2.** 2019 Upright design and it’s mass Properties

![Figure 3](image2.png)

**Figure 3.** 2020 Upright design and it’s mass properties
3.2. Design process and manufacturability

Numerous iterations were made to obtain the design shown below based on the results obtained on static analysis for Von Mises stress, stress flow, and maximum deformation. The uprights designed for race cars are required to have a high stiffness to resist the camber changes in the wheel assembly.

Manufacturability is one of the main factors considered while designing the upright. Generative design and additive manufacturing are the most preferred and most efficient ways to reduce the weight of any mechanical component as it gives much flexibility in designing and manufacturing. However, it has some drawbacks, like economic feasibility and manufacturing accessibility. These points play a vital role in a formula student team while designing and manufacturing a component. As this technology was not feasible and not accessible easily, the authors concentrated on a design that can be manufactured using traditional techniques.

4. Analysis

The analysis was done in Ansys Workbench 18.2. The details are discussed in the following sections.

4.1. Pre-processing:

4.1.1. Meshing: A tetragonal mesh was generated on the model, as shown in figure 4 below. The element size was kept as low as possible considering the computational power available for the analysis. The lower the element size higher the accuracy of the result [3]. The mesh parameters are as follows:

- Size Function = Proximity and Curvature
- Element Size = 12.21 mm
- Nodes = 706656
- Elements = 464159

More significant the number of nodes, the better the accuracy of the result. Keeping this in mind and considering the available computational power, the fine mesh was generated.

![Figure 4. Generated mesh (a) Front View; (b) Isometric View](image-url)

Figure 4. Generated mesh (a) Front View; (b) Isometric View
4.1.2. Boundary conditions: The boundary conditions and loading parameters are as calculated in the above sections of the paper. For the analysis of this design, the maximum loading condition in one of the dynamic events was considered. Autocross consists of different maneuvers like chicanes, slaloms, and hairpin bends. For analysis, the slalom part of the autocross is considered as the magnitude of the force is applied cyclically. Fatigue analysis is done concerning those parameters. The loading conditions and the forces applied are as shown in below figure 5.

![Boundary conditions](image)

**Figure 5.** Boundary conditions applied to the upright are as shown in the analytical calculations part.

4.1.3. Material selection and its properties: The material used for this design was Al 7075 T6. The material was selected for its low weight and high strength properties [4]. This material is aerospace-grade aluminium and is used to manufacture aerospace parts. The specifications and properties of the material are shown in figures 6(a) & 6(b).

![Aluminum 7075 T6 material properties](image)

**Figure 6(a)** Aluminum 7075 T6 material properties
4.2. Post-processing:

Static Structural analysis and fatigue analysis was carried out on the upright. The loading conditions for the analysis are as calculated and discussed above. Below are the analysis parameters and the performance results of the component.

The Equivalent or Von Mises Stress and the Total Deformation of the upright are as shown in figures 7(a) and 7(b).

![Figure 6(b) SN Curve of Aluminum 7075 T6](image6b)

![Figure 7(a). Equivalent stress or Von Mises stress](image7a)
As discussed earlier, the analysis is being done to keep in mind the maximum cyclic loading the upright will experience in the dynamic events in autocross. Autocross is a form of competition in which cars are driven around an obstacle course, typically marked out by cones. Slalom is a part of this autocross track which is to move or race in a winding path, avoiding obstacles [5].

Considering the cyclic loading in the above situation, fatigue analysis was done, and the results are as shown in figures 8(a) and 8(b). The fatigue analysis parameters are as follows [6][7]:
- Loading Type = Fully Reversed ; Analysis Type = Stress Life
- Mean Stress Theory = Goodman ; Stress Component = Equivalent (Von Mises)

![Figure 7(b). Total deformation](image1)

![Figure 8(a): Equivalent alternating stress](image2)
5. Results
The results from the above analysis are as shown in below table 2. It is essential to keep in mind the material properties, especially the maximum yield strength of Aluminum 7075 T6, to interpret the results better.

Table 2. Results from the above analysis.

| Parameter                                      | Value         |
|------------------------------------------------|---------------|
| Max. Equivalent Stress (Von Mises)             | 201.53 MPa    |
| Max. Equivalent Alternating Stress             | 201.53 MPa    |
| Min. Life or Number of Cycles                  | $5.3302 \times 10^5$ |

6. Conclusion
The iterative design process was followed while designing this upright. The previous design of the upright was used as a benchmark to improve the new design of the upright. Drastic improvements were made, and optimization was done. After a couple of iterations of design and analysis, an optimized design was achieved. The new design was 48.61% lighter than the previous design. This component is part of wheel assembly on all four wheels. Hence, this sums up to a total weight reduction of 48.61% in the wheel assembly sub-system of the car.

The structural and fatigue analysis of the upright was conducted, and it was observed that the component sustained the static and cyclic loading without any premature failure. Based on the above results, it can be concluded that the component is safe to be used in its application. Design optimizations made to the design based on the analysis results of the older designs have contributed to the weight reduction of the component without compromising the performance and safety of the upright. It was also observed that the stress life of the upright could be greatly enhanced by improving the geometry of the upright based on the stress-induced and stress flow. Considering the result of the study conducted, it can be concluded that major improvements in terms of fatigue life enhancement, performance prediction, vehicle reliability, weight reduction, and other design parameters can be achieved by carrying out the static and fatigue analysis of the components.
7. References

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