Design, Analysis and Optimization of a Brake Disc for 4WD All-Terrain Vehicle

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Abstract - *Disc brake system is one of the most advanced braking systems with the highest braking efficiency. It results in successfully stopping the vehicle at the minimum distance possible thereby increasing safety and performance. The Kinetic energy of the vehicle is converted into thermal energy due to the friction between the brake pads and the disc. Thus the brake disc becomes one of the most critical components of a disc brake system. Hence it is important to ensure its durability and performance using advanced computer-aided analysis tools. This research paper includes the designing of brake discs for a 4WD All-Terrain Vehicle and optimizing the design using analysis software such as ANSYS and Solidworks to majorly reduce weight while keeping the strength and temperature control at optimum level.*

Key Words: Brake disc, 4WD, SAE Baja, Inboard brakes, weight reduction, and topology optimization.

1. INTRODUCTION

A brake is a mechanical device that inhibits motion by absorbing energy from a moving system. It is used to slow or stop a moving vehicle or to prevent its motion, most often accomplished by friction. It is an energy converting mechanism that converts a vehicle's kinetic energy into heat while stopping the rotation of the wheels. All braking systems are designed to reduce the speed and stop a vehicle. Friction converts the kinetic energy into heat. The greater the pressure applied to the object's surface, the more friction & heat is produced, & the sooner the vehicle will be brought to rest. Kinetic friction acts in the brakes and static friction acts between the tire and road to slow down the vehicle. Most brakes commonly use friction between two surfaces pressed together to convert the kinetic energy of the moving object into heat, though other methods of energy conversion may be employed. For example, regenerative braking converts much of the energy to electrical energy, which may be stored for later use. Other methods convert kinetic energy into potential energy in such stored forms as pressurized air or pressurized oil. Eddy current brakes use magnetic fields to convert kinetic energy into electric current in the brake disc, fin, or rail, which is converted into heat.

1.1 Disc Brakes

The disc brake was first patented in 1902 by Lanchester Cars, however, it used copper brake pads which wore too quickly, and wasn't very practical. Various versions and adaptations were used until a disc brake that resembles what we see now - courtesy of Jaguar with their C-type race car - was introduced in the '50s. Jaguar first showcased the advantages of their disc brakes at Le Mans in 1953. The reduction in fade due to the open-disc design meant that the cars could brake later and harder than drum-equipped rivals. It wasn't until 1955 that a mass-production car came with disc brakes. The 1955 Citroën DS came with inboard front disc brakes. In the years that followed, disc brakes would become the norm on the front axle of road cars.

We now have various types of disc brakes with the most common type being the conventional cast-iron disc setup. Cheap to produce, and more than adequate for your average commuter, the cast-iron disc brake dominates the market. But what happens to cast iron brakes when abused, say for example, when used on sports cars? Cast iron disc brakes can suffer from 'brake fade' when used repeatedly and under high-speed conditions. This phenomenon comes in various forms and presents itself as a reduction in stopping power (mechanical fade) or a 'long' brake pedal (fluid fade). Mechanical fade is when the temperatures get so high, that a layer of gas can build up between the disc and pad, reducing stopping power. Fluid fade is when the same high temperature finds its way to the brake fluid which can boil. This changes the properties of the fluid meaning that the brake pedal can go to the floor, reducing braking performance.

1.2 Topology Optimization

Topology Optimization is used to optimize the distribution of material within the desired boundary known as the design space for a given set of load cases to maximize the performance along with minimizing the mass thus reducing the cost for manufacturing. Topology optimization utilizes a 3D design space and removes away material within it to achieve the most efficient design. The method doesn't care about aesthetics, traditional approaches, or any other of the usual design constraints that are normally used in the design. In conclusion, if we define the loading and the constraint system, it will figure out the material needed to develop that load path.

2. OBJECTIVES

The main objective of our analysis is to compare the results of the initial and final design of the brake disc through finite element analysis on Ansys software and verify the reduction in weight of the disc after optimizing it with the help of a topology optimization tool. The material selected for analysis is SS410 which is suitable for various parameters of the brake disc such as disc diameter, Pattern & Material composition. The static structural and thermal analysis will be conducted on both initial and optimized designs to evaluate the results.

3. MATERIAL SELECTION

We have selected stainless steel AISI 410 for our design. This material was selected considering the structural requirements, availability, machinability, and cost. Also, chromium content in the material helps with better thermal conductivity and is less prone to rusting at high temperatures. The properties of SS410 are as follows:-

Table -1: material properties.

Parameters	**Value**
Density	7750 kg/m^3
Melting point	1480-1530 °C
Specific heat capacity	460 J/kg·K 20 °C
Young's modulus	190-210 Gpa
Thermal conductivity	24.9 W/m·K at 100 °C

4. DESIGN METHODOLOGY

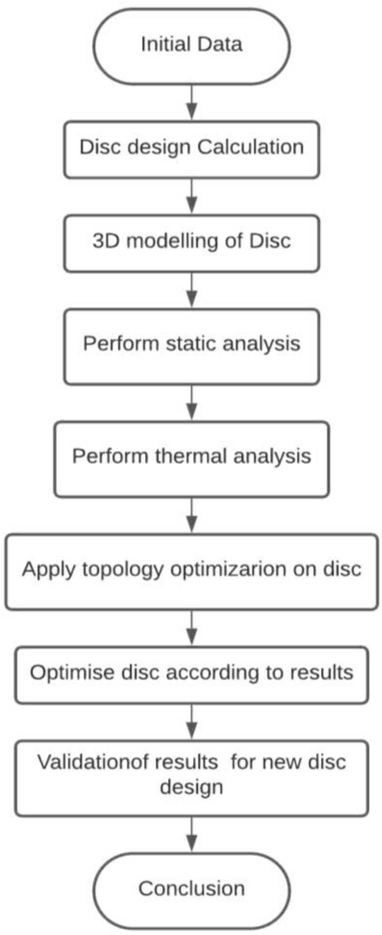

Chart -1: Single sampling plan

5. CALCULATIONS

Table -2: Prerequisites for calculations

Vehicle Weight (with driver= 60)	250 kg
Height of CG	22.50 inch
Wheelbase	58 inch
Tire Radius	0.29 m
Pedal ratio	6:01
Pedal Force	350 N
μ (rotor and pad)	0.35
μ (tire and gravel)	0.7
TMC Diameter mm	20.64
Force in TMC	2100 N
Area of TMC	334.59 mm^2
Calliper Piston Area	635.26 mm^2
Pad Area	2 inch^2
Pad Length	67.6 mm
Pad Breadth	25.4 mm
Deceleration	0.9 g
Weight Distribution	47:53:00

Static Weight

1. Front = (Vehicle Weight*47/100) - 117.5 kg

2. Rear = (Vehicle Weight*53/100) - 132.5 kg

Weight Transfer

Weight Transfer = Vehicle Weight*Deceleration*(Height of CG/Wheelbase) = 87.28448276 kg

Dynamic Weight

1. Front = Static Weight+Weight Transfer- 204.7844828 kg

2. Rear = Static Weight+Weight Transfer - 45.21551724 kg

Axle Load

1. Front = (Dynamic weight)*(9.81) - 2008.935776 N

2. Rear = (Dynamic weight)*(9.81) - 443.5642241 N

Torque on the wheels

1. Front = (Front axle load/2)*(Tire Radius) - 293.4050701 (Nm)

2. Rear = (Rear axle load/2)*(Tire Radius)-64.78255494 (Nm)

Force on TMC - 1925 (N)

Pressure generated in TMC - 5.75 (N/mm2)

Force in the circuit -

1. Front = 5600.689 (N)

2. Rear = 2559.47 (N)

Pressure generated in the circuit -

1. Front = 4.405 (N/mm2)

2. Rear = 2.013 (N/mm2)

Kinetic energy (absorbed by the disc) - 8109.133 (J)

6. INITIAL CAD DESIGN

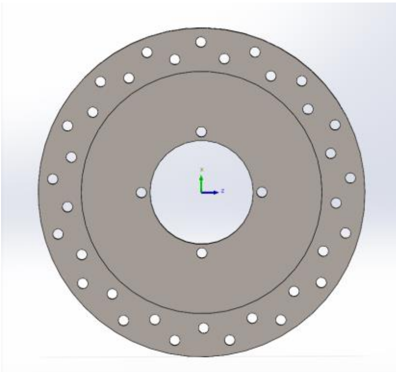

Fig -1: CAD model of the initial disc.

7. FEA ANALYSIS

7.1 Initial analysis

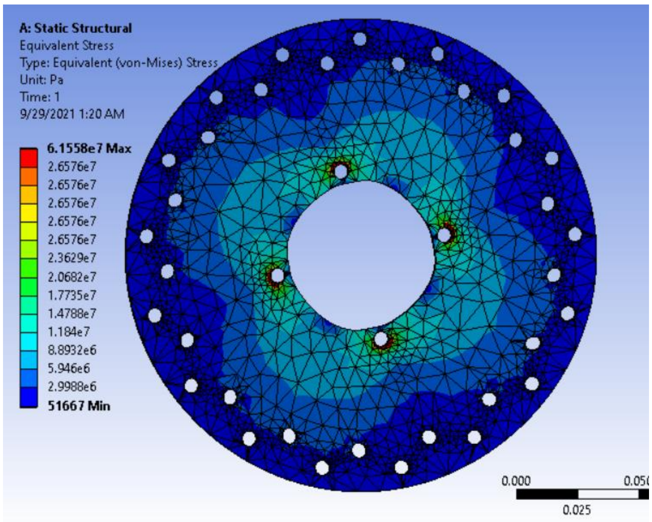

Fig -2: Equivalent stress of initial disc.

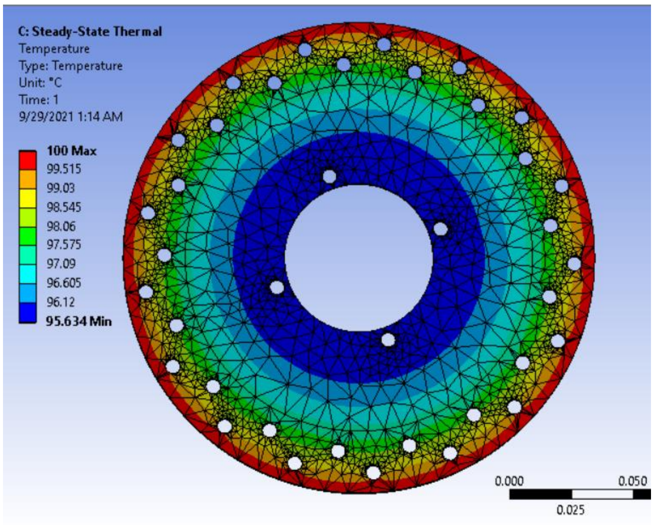

Fig -3: Temperature distribution.

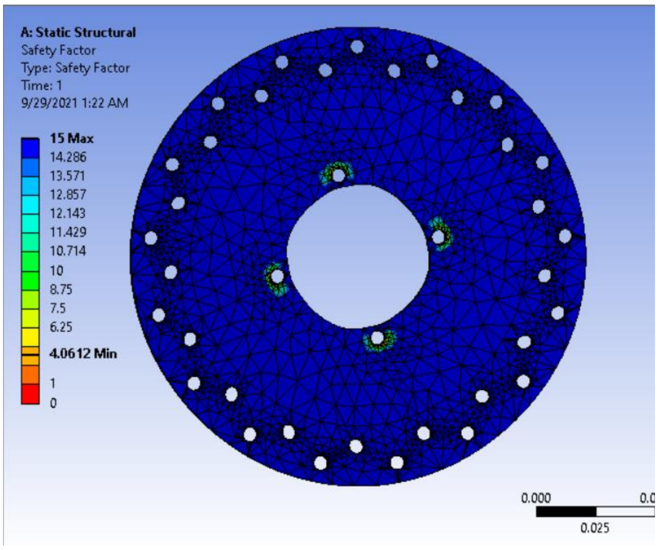

Fig -4: Factor of safety for the initial disc.

7.2 Topology Optimization

After the analysis, we proceed with topology optimization by combining both the factor of safety and the thermal load cases. Iterative Analysis and Optimization were carried out to get an optimum result. Topology Optimization was carried out in the same software as before i.e. Ansys 19.2. Topology Optimization has a range of results, we will be taking that result which suits our result for further analysis. Targeted weight reduction was at least 35% of the total mass of the disc. The figure below shows one of the solutions from the range of topology optimization.

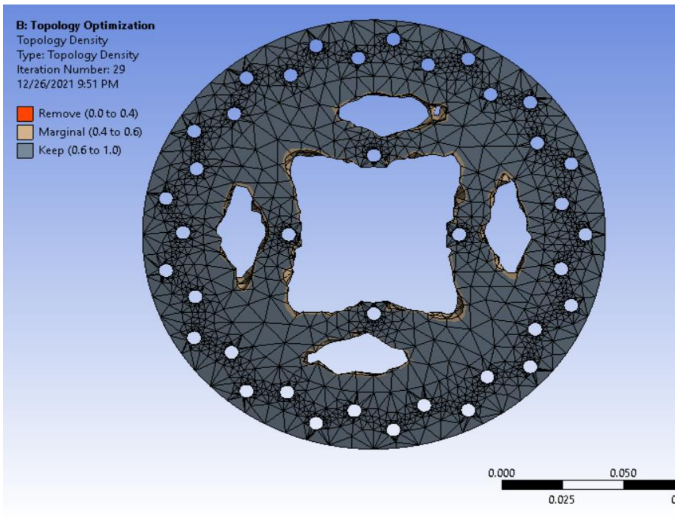

Fig -5: Topology optimization.

Hence by observing the removable area of the disc a new design was created and analyzed in Ansys 19.2 for validation of previous results.

7.3 Optimized brake disc

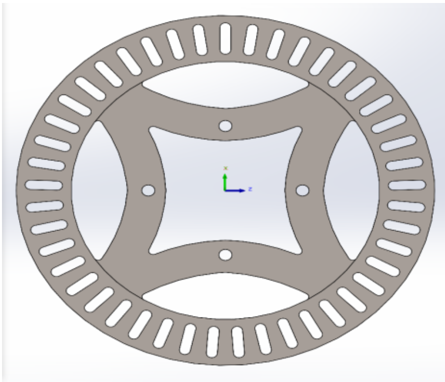

Fig -6: CAD model of initial disc

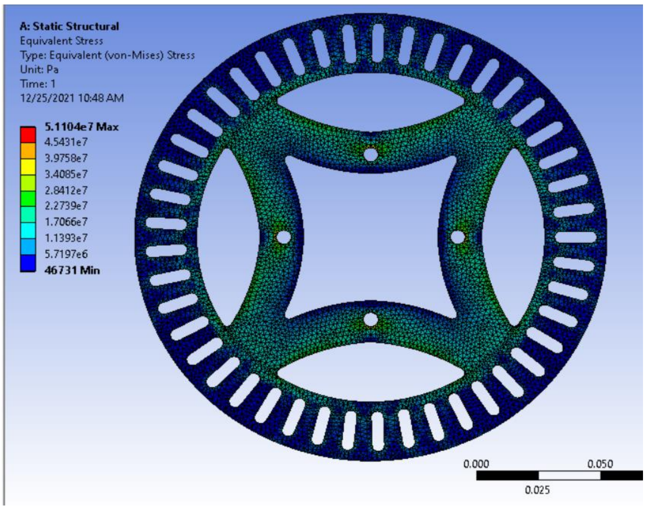

Fig -7: Equivalent stress of final disc

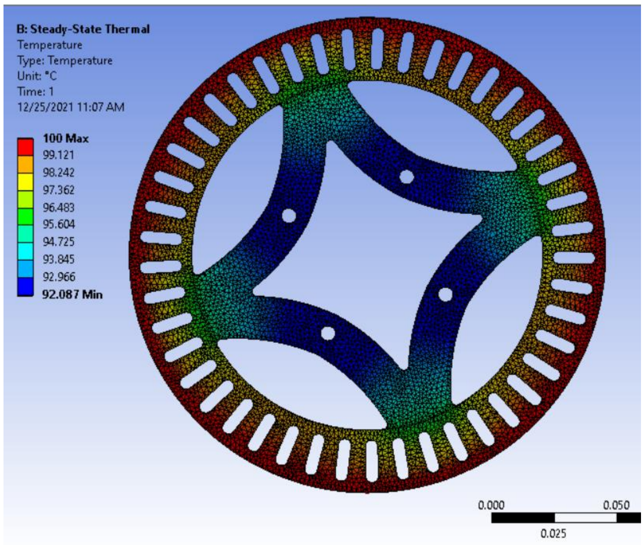

Fig -8: Temperature distribution

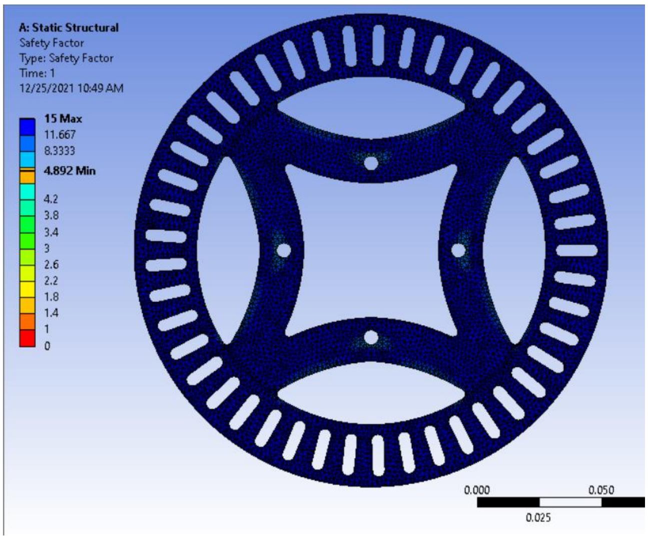

Fig -9: Factor of safety for the final disc.

8. RESULTS

Table -3: result table.

Parameters	Before optimization		After optimization	
	Minimum	Maximum	Minimum	Maximum
Mass (g)	-	761	-	493.18
Equivalent stress(MPa)	0.051	61.558	0.046	51.104
Total (mm) deformation	0	0.0599	0	0.0158
Factor of safety	-	4.0612	-	4.892
Temp. °C	95.6	100	92	100

9. CONCLUSION

It is evident that there was a significant reduction in the weight of the brake disc of about 35%. It is also observed that stress and deformation were reduced in the optimized design. Also increased surface area due to the addition of slots in the contact patch has led to better heat dissipation and lower disc temperature.

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