Design, Analysis and Optimization of a Self Locking Clutch Type Differential for a Race car

Pulkit Dubey[1], Vinit Dhamne[2], Shailendra Dayane[3], Shubham Kale[4], Chaitanya Deshmukh[5]

[1,2,4,5]*UG Student, School of Mechanical Engineering, MIT WPU, Pune, Maharashtra, India*
[3]*Assistant Professor, School of Mechanical Engineering, MIT WPU, Pune, Maharashtra, India*

Abstract - *The main function of differential is to provide Torque & RPM differentiation depending upon characteristics of different differentials. Goal of this project is to design a differential for significant weight and performance gains and also maximize and improve traction utilization for a high performance race car. Differential torque biasing is influenced by a number of factors, including clutch packs, preload, ramp angles adjustments. The fundamental parameters for this project is acquired and bound by the rules and regulations specified for a fsae vehicle. Using Design Methodology, a cad model was developed which was then analyzed on suitable FEA software.*

Key Words: Locked Differential, Open Differential, Limited Slip Differential, Clutch Plate Type LSD, Vehicle Dynamics, Race Car

1. INTRODUCTION

When taking a corner naturally the outside wheel traces a longer distance than the inside wheel. Since speed is equal to the distance traveled divided by the time it takes to go that distance; the wheels that travel a larger distance travel at a higher speed and so the outside wheel must spin faster. And this is the reason as to why almost every car has one or more differentials in their driveline.

The differential is a set of bevel gears that transmits engine power to the wheels while allowing splitting of the engine torque two ways, allowing each output to spin at a different speed.

Mechanical differentials are divided into three categories:

1. Locked Differential-Spool
2. Open Differential
3. Limited Slip Differential

1.1 Locked Differential-Spool

A spool is a simple axle with locked differential that basically couples the two rear wheels so that both wheels are forced to rotate at the same angular velocity. The spool is extremely lightweight and has high reliability due to its mechanical simplicity. Running a spool however has some drawbacks; specially, during cornering (more prominent at low speeds) - the vehicle would experience understeer i.e. where the car turns less than it is expected to. This is because a vehicle with spool will want to fight against the direction of steering since both driven wheels are pushing forward with equal force. The effects are accelerated tire wear, increased power consumption, and greater steering effort.

1.2 Open Differential

The open differential is universally adopted on passenger cars to address this cornering issue of a spool by decoupling the angular velocities of the drive wheels. The open differential using an arrangement of bevel gears can deliver torque to both wheels that are free to rotate at different velocities. Since in this case the torque is always equal on both sides torque transmission has no direct impact on vehicle handling, cornering balance, or driver inputs. However a traction problem is encountered if slipping ever occurs. It will send the majority of the power to the slipping wheel the moment a wheel loses traction and so the car is not pushed forward when it is experiencing wheel slip.

1.3 Limited Slip Differential

To overcome this downside of spool and open differential, Self-Locking or Limited Slip Differential is used. A passive limited-slip differential is based on mechanism in which some sort of clutch packs and ramp angles in parallel with an open differential is used which offers the potential to cover the entire working range between the open differential and the spool. It can be quite effective for racing cars, solving the traction problem on one side and improving vehicle balance and stability on other side.

The two most common types of passive LSD's are Speed-sensitive differential and torque-sensitive differential.

1. Speed-sensitive differential:

As name suggests, the locking torque is a function of the angular velocity difference across the differential. A typical device consists of open differential and rotary viscous coupling, basically a clutch pack immersed in a silicon-based fluid. The system affects vehicle maneuverability to a limited extent. As building up a speed difference takes time there is certain delay in the torque transfer response thus for high-performance applications this device is not very suitable to improve vehicle handling and stability.

2. Torque-sensitive differential:

The most common torque-sensitive device on road-going sports cars and racing cars is the Clutch Plate type (Salisbury) Differential or Plated Differential. Though this differential is much more complex we find the adjust-ability of the plated LSD a big upside in a motorsports application.

Upon acceleration, the spider axle is wedged into the inclined surfaces called ramps of the side gear pressure rings, with a component of the resultant force in such a way that it pushes those outwards and compresses the clutch plates. As the pressure increases and so larger friction on the clutch plates increasingly binds the driven wheels as more acceleration is applied making it very hard for them to spin at different rates. So ramp angles determine how much pressure is applied to the clutch plate to increasingly bind the wheels. The shallower the ramp angle, the more aggressive the locking characteristics. For example, a 45-degree ramp angle will lock up more aggressively than a 60-degree ramp angle, whilst a 90-degree ramp angle will not show any locking characteristics at all.

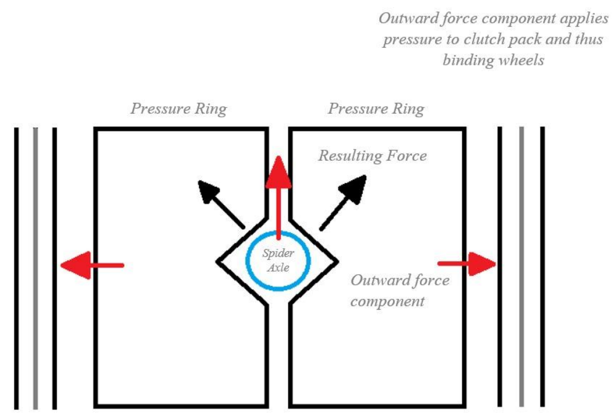

Fig - 1: Force Components while deceleration

Smaller the ramp angle, more spool-like behavior we will observe for higher powered vehicles during acceleration. In this case, it limits the slip to a greater extent sending power to the wheels with good traction. But then car will experience more understeer.

On the coast side, larger locking induces better braking stability, however, this also comes at the expense of understeer during braking.

Hence, finding the perfect spot for acceleration as well as coast ramp angles is key.

Based on the behaviour of the LSD under acceleration and braking, we have three different choices namely 1 way, 1.5 way, and 2 way. A 1-way differential only locks in acceleration, while a 2-way differential locks equally under acceleration or braking. For a 1.5-way differential, the ramp angle on the acceleration side is different to that on the braking side. A 1.5-way will lock under acceleration and partially under deceleration as well.

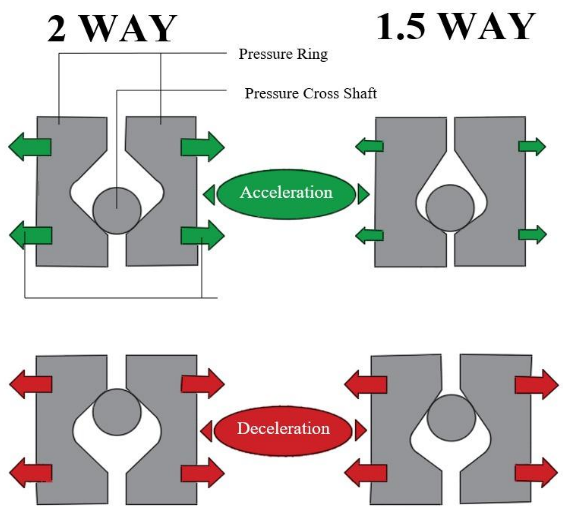

Fig - 2: 1.5-way and 2-way differential

An axial preload is often applied statically to the clutch packs by means of a Belleville spring to apply a minimum pressure to the clutch plates, and so the wheels are always coupled via friction to some extent. This baseline resistance must be overcome by the torque difference in the wheels before it can be able to spin at different rates. And this preload is second important parameter that can be tuned; first one being a ramp angle.

A number of other factors which influence the locking characteristics of plate LSDs are belleville washer characteristics, plate friction materials and the number of mating plate surfaces. External factors such as the vehicle weight, its distribution, traction of the tyres, and the engine power also influence how good the differential locks.

1.3.1 Clutch Pack

The clutch pack constitutes a series of friction disc and steel plates packed between the side gear and differential casing. While the friction discs are locked together with the side gear, the steel plates have tabs which are slotted into the grooves of the differential casing which rotates with the case. The friction plates are covered with cork type material which has high coefficient of friction. So when the clutch pack is well pressed, the frictional force between them causes it to move as a single solid unit. This motion is directly passed into the corresponding side axle.

To alter the number of active clutch interfaces; the order between friction disc and clutch plate can be varied. In general, the clutch plates and friction discs alternate i.e. in 0101 fashion. However, 0011 is also possible, since it reduces the active clutch plates in this case and thus decreasing the resistance, making it to operate as even more 'open'.

2. PROBLEM STATEMENT

The goal of this research is to examine the requirement for a light-weight limited-slip differential with several tunability options. Because of this, the ones that are currently available are either excessively expensive or do not meet the weight and tunability requirements. To solve this problem, we began by learning about the differential concept, including how the differential works mechanically, numerous viable solutions, and the impact of these factors on the differential system's overall performance.

As a result, differential analysis and modelling are used to assess the importance of clutch plates, friction discs, and preloads, as well as to apply higher-level optimizations such as adopting newer materials and incorporating several ways to reduce the overall weight of the subsystem.

3. METHODOLOGY

3.1 Gear Calculations

No. of teeth on Spider Gears, z_p	11
No. of teeth on Side Gears, z_g	15
Module Selected	2 mm
Pitch Cone Angle of Spider Gear, γ_p	36.25°
Pitch Cone Angle of Side Gear, γ_g	53.75°
Pitch Circle Diameter of Spider Gear, d_p	22 mm
Pitch Circle Diameter of Side Gear, d_g	30 mm
Pitch Cone Distance, A_0	18.6 mm
Material Used	18CrNiMo7-6
Ultimate Tensile Stress, S_{ut}	1100 N/mm^2
Beam Strength, σ_b	366.66 N/mm^2

By using formula of Effective Load and Buckingham's equation for dynamic loading, we got factor of safety as 1.98.

Hence, our design is safe.

3.2. Selection of heat treatment for gears

3.2.1 Carburizing

Given the qualities of high ductility and great core strength, we chose low carbon steel. Gears made of 18CrNiMo7-6 should have a hardness range of 60-70 HRC. Carburizing is the greatest way to obtain such hardness while maintaining core strength. Carburization is a surface hardening procedure that can surface harden an element up to 6.35mm deep into the surface. The depth is mostly determined by the carbon percentage induced by the soaking duration. It increases the material's wear resistance. Carbon is infused into the steel during carburization, which is done at temperatures between 910 and 950 degrees Celsius.

The ferrite/ pearlite core helps to enhance the carbon-rich surface.In applications where components are subjected to stress loads, vibration, and misalignment, case hardened steel is chosen. Case hardened low carbon steels and alloy steels, unlike through hardened steel, become tough, strong, and hard without becoming brittle. Case hardening also produces a wear-resistant surface that is long-lasting and dependable.

3.2.2 Tempering

After carburization comes tempering, which is an annealing process. After carburization, steel becomes exceedingly hard and brittle, thus it goes through another process to reduce its hardness and increase its ductility while keeping its microstructure same. Tempering a steel below its critical temperature preserves its martensitic structure, but if tempered for a long time, it transforms into a mixture of ferrite and small carbides, the size of which is determined by the tempering temperature. As a result, the steel becomes softer and more ductile. Temperature and time are the most important tempering parameters, and they must be accurately managed to get the desired ultimate hardness. Lower temperatures keep hardness high while reducing internal tensions, while higher temperatures soften the material.

Figure 3: Hardness of 60 HRC of spider gear

3.3 Optimum Lap- Point Mass Simulation

For this particular simulation, input parameters are weight, aero model, tire data, motor rpm and torque, gear reduction ratio and final drive ratio.

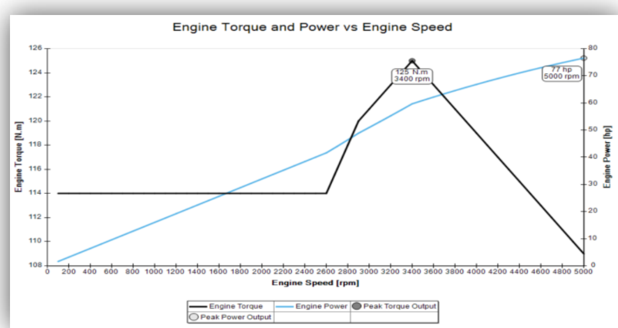

Figure 4: Engine Torque and Power vs Engine Speed

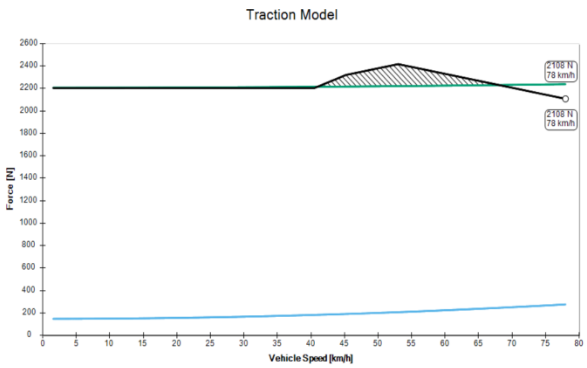

Figure 5: Force vs Vehicle Speed

3.4 Detail step-by-step Procedure

The primary step was to know the load transfer and lateral acceleration values. For this, the vehicle was equipped with locked differential and was driven on a course, having hairpin, of minimum radius of 4.5m. This course was set with respect to the regulations provided by the competition official's .The vehicle was attached with accelerometer and was placed at the centre of gravity of the car.

Logged acceleration data helped us find the mode acceleration value and deduce the corresponding maximum load transfer value for that mode acceleration.

Weight transfer calculations:

The lateral load transfer is found from the following formula:

$$\Delta w = \frac{a_{y \times m \times h}}{T_d}$$

It depends on various vehicle parameters such as height of centre of gravity from the ground and front axle, track width and load distribution.

Since we are aware of the load transfer experienced during lateral acceleration and static load on each rear wheel; tractive force can be found by multiplying the friction coefficient with wheel load and lateral acceleration at that instant.

From longitudinal tractive force, tractive torque at each wheel was found. The ratio of torque on rear wheels gave us the torque biasing ratio at the instant of maximum lateral acceleration.

Torque Carrying Capacity of Clutch Packs:

The torque transmitting capacity of the clutch packs used in the differential can be given in the following equation:

$$\Delta T = \frac{2}{3} \times \left(\frac{C_m}{r_{ramp}} \times \cot \sigma\right) \times \left(\frac{R^3 - r^3}{R^2 - r^2}\right) \times n \times \mu_c$$

In order to keep the torque difference constant, we have iterated the mentioned parameters on the right hand side of the equation.

After accumulating the requisite parameters such as dimensions, final drive ratio, running torque and considering packaging and various other constraints, a cad model was developed as shown which was then analysed on FEA software's.

4. RESULTS AND DISCUSSION

4.1 Cad Models

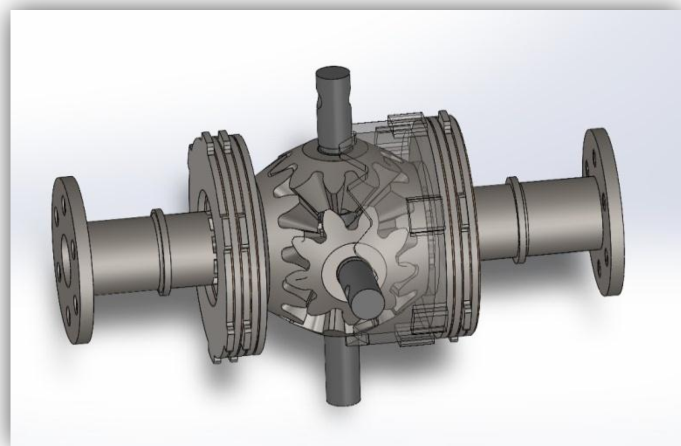

Figure 6: Assembly without Casing

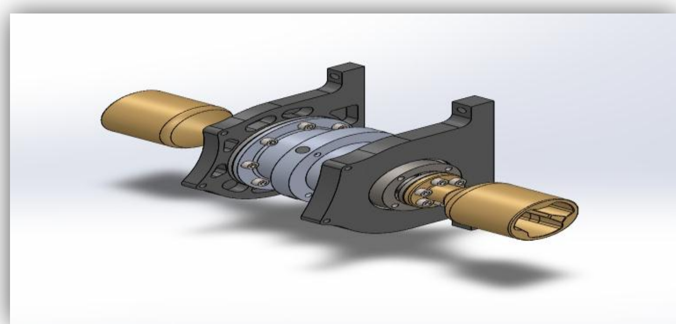

Figure 7: Assembly with Casing

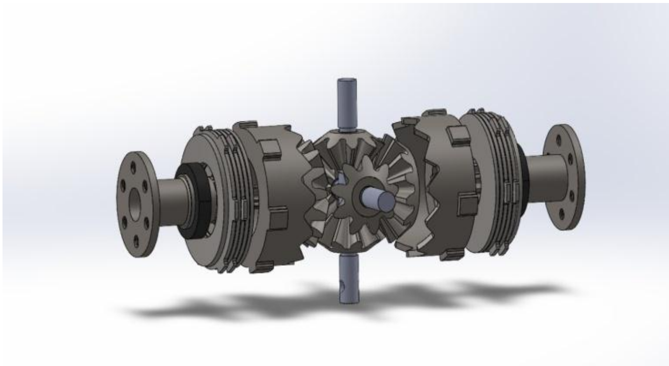

Figure 8: Exploded View of Clutch type LSD

4.2 Analysis

4.2.1 Analysis of Spider Gear

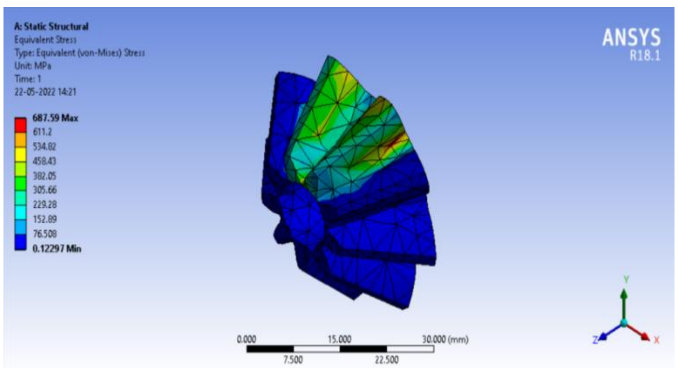

Figure 9: Stress Analysis of Spider Gear

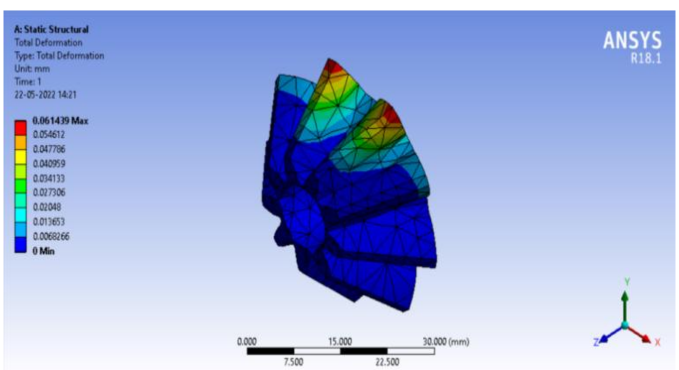

Figure 10: Deformation Analysis of Spider Gear

4.2.2 Analysis of Side Casing

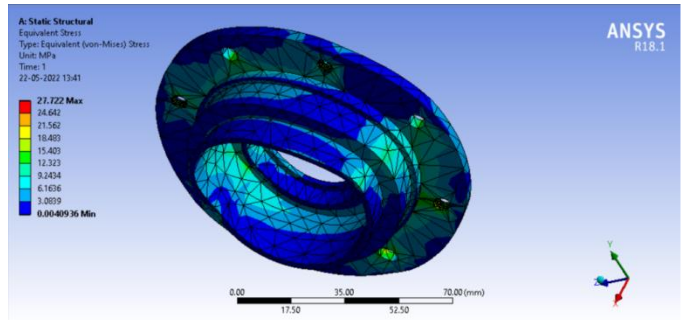

Figure 11: Stress Analysis of Side Casing

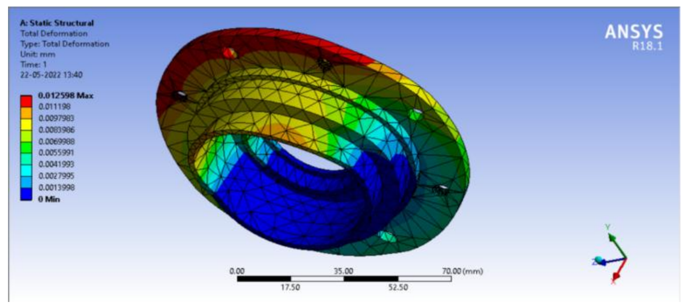

Figure 12: Deformation Analysis of Side Casing

Solidworks 2021 was used to model all of the cad files, and Ansys Workbench 18.1 was used for analysis. The above results were obtained by simulating the load case with torque coming through the final drive on the differential. The gears are made of 18CrNiMo7-6, and the casing is made of aluminium 7075 T-6. The properties of 18CrNiMo7-6 grade steel are superior to C15 or 20MnCr5 grade steel in terms of yield strength, tensile strength, impact value, and percentage of area reduction. As a result, the material can withstand a large amount of load with minimal bending stress, reducing wear and increasing tooth life, significantly increasing product life and efficiency.

5. CONCLUSION

The effectiveness of the limited slip differential must be tuned to fulfil various types of driving situations, as shown in the previous discussion.

First, the unit's traction enhancements must provide appropriate traction performance to suit the extreme racing expectations in the most difficult circumstances. The shape of the bias ratio curve required to meet the vehicle performance needs will then decide the type and number of clutch assemblies to be used. Many of these different combinations need to be evaluated depending upon various parameter including traction, vehicle setup etc.

The current paper reviews the working principles of differentials, design, benefits, analysis of limited slip differentials, with a focus on the ramp differential and clutch plates which is still the industry standard in professional motorsport.

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BIOGRAPHIES

Mr. Pulkit Dubey is currently pursuing his Final Year B.Tech course in the School of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India.

Mr. Vinit Dhamne is currently pursuing his Final Year B.Tech course in the School of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India.

Prof. Shailendra A. Dayane is currently working as an Assistant Professor in MIT, Pune since the year 2000. He is a graduate from VNIT, Nagpur.

Mr. Shubham Kale is currently pursuing his Final Year B.Tech course in the School of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India.

Mr. Chaitanya Deshmukh is currently pursuing his Final Year B.Tech course in the School of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India.