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Design Methodology of a Custom Limited Slip Differential for an FSAE Vehicle

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Abstract - *The role of differentials in the current motorsports community is quite significant in terms of handling and drivability of the vehicle. Limited slip differentials are quite popular in the racing community today due to its dynamic advantages over other differentials. In India, the availability of limited slip differentials is quite limited for motorsports. The objective of the presented work is to develop an optimum methodology to design an efficient Custom Limited Slip Differential for a Formula Student Vehicle. Entire work was performed under the Formula Student rulebook restrictions and guidelines for an efficient system buildup accompanying optimum design. The paper enlists various steps adopted for the design of the custom differential including data acquisition.*

***Key Words*: Limited Slip Differential, Locked Differential, Open Differential, Methodology, Clutch Type LSD, Vehicle Dynamics.**

1. INTRODUCTION

When a vehicle initiates a turn, it's quite evident that both the rear wheels follow different arcs (the outer wheel follows a different arc as compared to the inner one), hence both the rear wheels have to cover different distances for a given time frame which implies that both the rear wheels need to rotate at different speeds. This is the scenario where differential comes into picture. Differential plays an immense role in the turning of your car. Let us consider that a rear wheel drive car is turning left, then logically the left wheel should rotate at a lower speed and the right wheel should rotate at a higher speed. The differential is designed in such a way that both the wheels on the axle can rotate at different speeds allowing the car to take a smoother turn.

There are mainly 3 types of mechanical differentials:

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

1.1 Open Differential

Open differential is the oldest and most commonly used differential across all types of cars. The reason being its reliability, simplicity and cost effectiveness. The engine powers ring gear on differential casing which further transmits it to the wheels via a pair of side gears and set of spider gears. Despite its wide usage, open differential has some limitations. All the power coming from the engine is sent to the wheel having least traction. So if one wheel of a car is stuck in mud, then all the power is sent to the same wheel. This makes the vehicles having open differential very unsuitable for off-road and racing purposes.

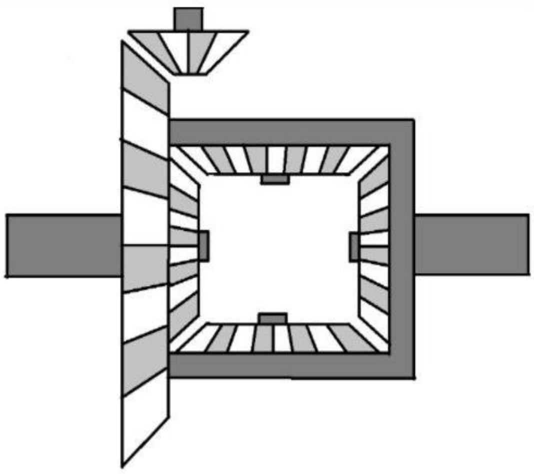

Fig - 1: Open Differential

1.2 Locked Differential

A locked differential (Also referred to as spool), limits both the wheels to rotate at same speed irrespective of any scenario. Unlike an open differential, a locked differential has the potential to provide 100% of the input torque to the wheel with high traction when the other wheel with low traction starts slipping. The major problem with a locked differential is that the vehicle would experience a considerable amount of understeer (since both the wheels spin at same rotational speed) with high tire degradation. It is widely used in go carts and V8 supercars. Spool differentials were a popular choice in the racing community before the introduction of limited slip differentials.

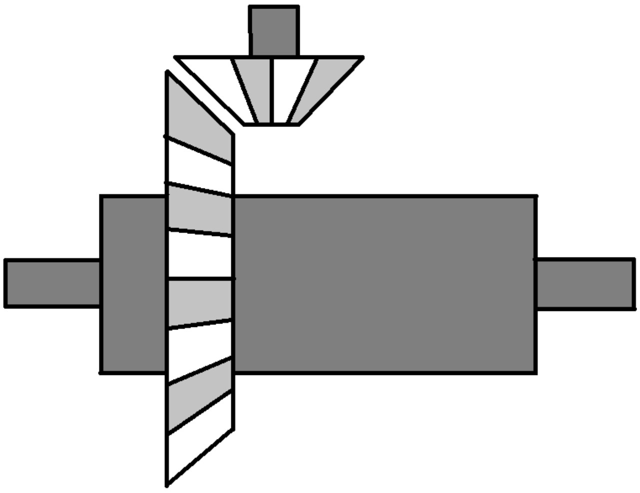

Fig - 2: Locked/Spool Differential

1.3 Limited Slip Differential

Since open differential transfers all the power to the wheel having less traction, getting out of low traction surfaces is difficult. Thus, LSD has a mechanism such that it transfers power according to the traction on the wheel.

The clutch-plate type LSD has all of the same components as an open differential, but it adds a spring pack or conical washers and a set of clutch packs. Some of these use flat disc clutches while others use a cone clutch similar to a synchronizer in a manual transmission. The clutch pack gets engaged and the left and right side of the axle gets locked together when a wheel with least traction starts slipping. This system is preferred in high-performance race cars.

A limited slip differential is designed to distribute as much power to the drive wheels as possible, while maintaining excellent handling characteristics for high speed driving. The clutch-plate type mechanical LSD is most often selected for this application because of its simple design, durability and ease of adjustment.

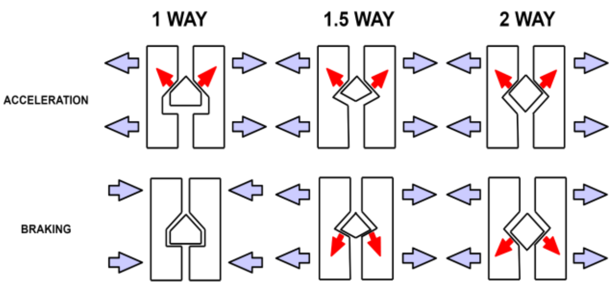

Fig - 3: 1-way, 1.5-way & 2-way differential

When you select a Limited Slip Differential (LSD) you will have the choice of a 1-way, 1.5-way, or 2-way differential. A 1-way differential only provides differential lock up during acceleration, a 1.5-way differential will lock under acceleration and partially lock under deceleration, and a 2-way will lock equally under acceleration and deceleration (engine braking, releasing the throttle).

A 1.5-way LSD reduces the force that locks the differential together than if it were to be a 2-way LSD under deceleration. Having a 1.5 or 2 way reduces the likelihood of one tire from stopping (while one tire is still rotating) than a 1-way. If you're going around a corner while decelerating, a 1.5-way may be better over a 2-way, so that your tires still transfer some torque, but also allow for different wheel speeds so that one tire is not dragging or skipping.

Engine braking is mostly responsible for lock up of the differential during braking. This majorly happens when the driver goes off throttle. The locking force continues as long as the driver remains off throttle. While in neutral and decelerating scenario, the differential will act as an open differential, irrespective of it being a 1-way, 1.5-way, or 2-way LSD.

How quickly and how well a differential "locks" is determined by the ramp angles, the horsepower of the car, and the amount of available grip. Steeper ramp angles, more power, and/or more grip will cause a differential to lock more quickly and effectively; Shallower ramp angles, less power, and/or less traction will cause a differential to lock up less quickly and effectively.

How much a differential actually locks is determined by the clutch plates. The more clutch plates you run, the more the differential will lock when it's fully engaged. The manufacturers often give recommendations for 100% lock, 80% lock, and 60% lock, which is very useful for tuning the differential for different surfaces and applications. Finding the perfect balance between ramp angles and clutch plates will make an enormous difference as far as how the car accelerates and will also directly affect the handling.

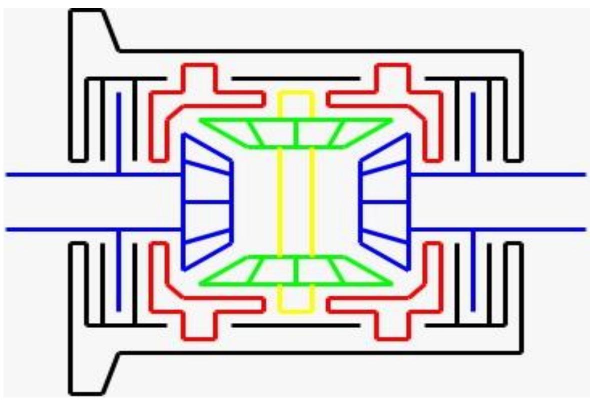

Fig - 4: Clutch-plate Type Limited Slip Differential

2. Problem Statement

In the year 2020, our formula student team switched from Combustion Vehicle (CV) category to Electric Vehicle (EV) category. This led to an increase of 70kg in weight. As there was no multi speed gearbox, the torque imparted by motor to wheels was halved from 800Nm to 450Nm. To accommodate the EV powertrain, the wheelbase was increased by 50mm leading to reduction in yaw inertia. This compromised the maneuverability of the vehicle leading to a dynamically slow car. This problem could be solved by using a limited slip differential instead of a locked differential.

3. Objectives (In decreasing order of importance)

3.1 Reliability

The most important goal was to develop a concept of a Limited Slip differential which would clear all scrutiny tests and successfully complete all dynamic events without any problems.

3.2 Drivability

Focus is given on good driver ergonomics and an interface that would allow the driver to respond quickly to the feedback received from the car; empowering him to extract the most out of the car and improve lap times. Improving the handling of the vehicle was also one of the major focus points.

3.3 Simplicity

With emphasis on simple concepts and part count reduction, the team is aiming at maximizing time for testing various components of the system.

3.4 Manufacturability

Designing components to aid accurate, simple and fast manufacturing to maximize testing time and ensure easily replaceable parts.

3.5 Weight

Reducing the weight of the system is important for a vehicle in order to extract maximum performance out of the vehicle (Since reducing the weight will result in increasing acceleration of the vehicle making it faster).

4. Methodology

4.1 Data Acquisition

The first step to consider while designing a differential is to acquire data from the car. For this process we drove the car on a figure of eight with the tightest turning circle admissible by the competition authority. For us the minimum turning radius was 4.5m. The driver was instructed to drive out of the corner in the fastest way possible on a locked differential. An accelerometer was placed near to the center of gravity of the car. Lateral acceleration with respect to time was logged.

4.2 Logging Maximum Lateral Acceleration

The corresponding data was acquired on the track and the major aim of logging lateral acceleration was to find the mode value of lateral acceleration which in turn helped us to find the maximum amount of load transfer corresponding to the mode acceleration value.

4.3 Weight Transfer Calculations

Lateral load transfer majorly depends on the static load distribution, track width, height of center of gravity of the vehicle from the ground and lateral acceleration experienced by the vehicle. So the lateral load transfer can be found using the following formula for the mode value of lateral value of lateral acceleration that we found using DAQ:

$$\Delta W = \frac{a_y \times m \times h}{T_d}$$

The corresponding load transfer was considered and load on each rear wheel was found.

4.4 Tractive Force from Tire Model

For that instant, we had the load on each rear wheel and the Pacejka tire model has graphs which involves the curve for the longitudinal tractive force vs longitudinal slip available at the tire for a given load. Since we are aware of the load at the instant of maximum lateral acceleration and longitudinal slip at that instant can be easily found using proximity sensors at the rear wheels and vehicle speed sensor at the estimated center of gravity of the car, we could easily plot the corresponding value of longitudinal tractive force at that instant on the rear wheels. Hence we can find the tractive frictional force at each wheel.

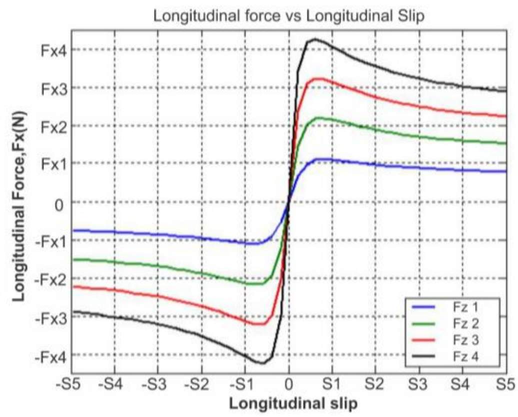

Chart 1: Longitudinal Force Vs Longitudinal Slip

4.5 Torque Difference on Wheels

Since we have the longitudinal tractive force at the wheel, multiplying it with the tire radius will give us the tractive torque at each wheel. And further getting the torque difference is possible. Since we have torque value at each wheel we can easily take the ratio of both, this can also be referred to as the torque biasing ratio of the vehicle at the instant of maximum lateral acceleration.

4.6 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:

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

We can iterate the mentioned parameters on the right-hand side of the equation in order to keep the torque difference on the left hand side of the equation to be constant.

4.7 CAD Model

After several calculations and selecting the appropriate values on the right hand side of the above equation based on the packaging and other design constraints we can finally proceed with the Cad model of different parts as shown and get them analyzed on different FEA softwares.

Fig - 5: CAD Model

Fig - 6: Exploded view of CAD Model

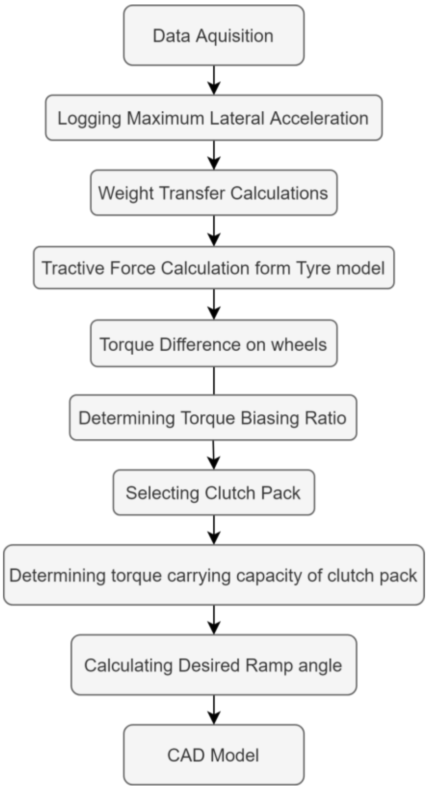

Chart 2: Process flowchart

Fig - 7: Inner Assembly Without Casing

5. CONCLUSIONS

This paper sums up the basic design methodology and analytical concepts related to the custom clutch type limited slip differential used in a Formula Student Car. After certain analytical calculations and considering the design constraints the CAD model of the custom differential was modelled in Solidworks. Integral assemblies were also modelled on solidworks and optimized accordingly in order to get a high performance differential as an output. **Chart 2** summarizes all the required steps in order to develop a high performance custom differential.

6. Nomenclature

ΔW= Amount of lateral weight transfer.

a_y= Lateral Acceleration.

m = Mass on rear axle.

h = Height of center of gravity from the ground.

T_d = Track Width of the vehicle.

ΔT= Differential locking or torque difference.

F = Force acting on the ramp pressure ring.

C_m= Differential input torque,

R = Outer radius of clutch plate.

r = Inner radius of clutch plate.

σ= Ramp angle.

n = Number of clutch disk interfaces (per side).

μ_c= Coefficient of friction between the clutch packs.

Fx = Longitudinal tractive force.

Fz = Weight on each wheel.

S = Longitudinal slip.

r_{ramp} = Ramp radius.

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