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Selection, Design & Analysis of Types of Differentials for Formula Student Vehicle Transmission

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Abstract - *The purpose of this paper was to select, design & analysis the differential transmission system for 2022 Formula student vehicle for Team Stallion Motorsport Electric. The role of differentials in the Formula Student vehicle is quite important in terms of handling and performance of the vehicle. Types of differentials are much popular in Formula Student Society due to its dynamic advantages. While keep in mind the team goal, the different teams use different type of differentials. Some of excellent teams, design their own custom differential for good dynamic performance which helps them to move towards best dynamic performer of the event. In India, the knowledge of different types of differentials and its performance is limited. The objective of this paper is to guide other formula student members to select the best differential for their vehicle according to their requirement. The complete work was done under the Formula Student rulebook restrictions and guidelines for an effective system making accompanying optimum design. The paper enlists different steps used for the selection and design of differential for Formula Student Vehicle.*

Key Words: **Formula Student, Differential, Stallion Motorsport, Spool Differential, Open Differential, Locked Differential, Limited Slip Differential, FS Rulebook, Biasing Ratio, Clutch type, Sun gear, Spring pack.**

1.INTRODUCTION

While designing, developing and testing any vehicle, the differential plays an important role. When a vehicle gets a turn, we see that both the rear wheels follow different arcs path. The outer wheel follows greater arc path as compared to the inner one, hence in the rear-wheel-drive vehicle both the rear wheels have to cover different distances for a given time which means that both the rear wheels have to rotate at different speeds. This is the reason why differential enters into picture. Differential plays a vital role in the turning of your car.

There are basically 4 types of differentials which we are going to study which is mainly used in formula student vehicle:

1. Spool differential
2. Open Differential
3. Locked Differential
4. Limited Slip Differential

1.1 METHOD OF APPROACH

The study of each type of differentials are done from various reference books. The differentials are divided into various categories as per there applications, and select one differential as per our requirement for design and analysis. The Designing of each component was done in SolidWorks software. The Factor of Safety Distribution and stress concentration analysis of each component of differential was done in Ansys software.

All our final results are verified with all the calculations and software's. While finalizing the performance and durability of the component we used the datasheets available with each material and components.

1.2 REQUIREMENTS IN DIFFERENTIAL IN FORMULA STUDENT VEHICLE

1. Rotate both wheels independently.
2. Working at traction condition.
3. Adjustable biasing ratio.
4. Amount of Torque transmitted to wheel

2. SELECTION OF TYPES OF DIFFERENTIALS

2.1 SPOOL DIFFERENTIAL

A spool is a type of differential that connects the single axle directly to the both wheels. Result in equal rotation of both wheels, due to that turning become unmanageable in wet or snowy weather. Spools are usually reserved for off road competition vehicles. A spool is the strongest means of locking the shaft or an axle, but unable to differentiate wheel speeds, transferring high stress on all drivetrain components.

Spool provides 100%-100% torque to both the wheels.

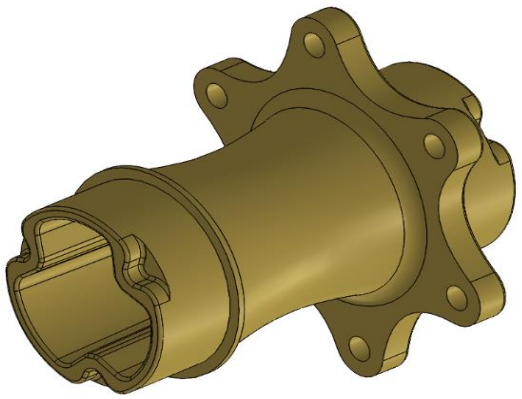

Fig -1: Spool Differential

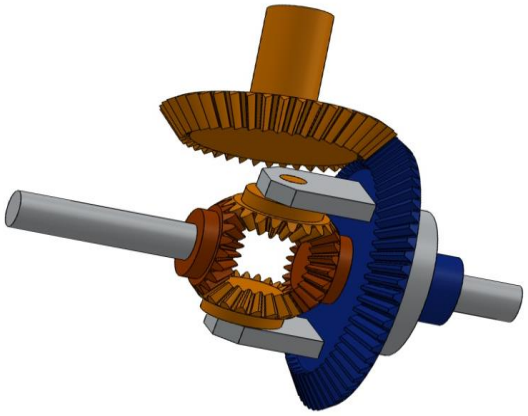

Fig -2: Open Differential

Table -1: Spool Differentiable Specifications

Rotation of both wheels independently	NO
Working at traction condition	NO
Adjustable biasing ratio	NO
Amount of Torque transmitted to wheel	100%-100%

Table -2: Open Differentiable Specifications

Rotation of both wheels independently	YES
Working at traction condition	NO
Adjustable biasing ratio	NO
Amount of Torque transmitted to wheel	50%-50%

2.2 OPEN DIFFERENTIAL

A differential is available in its most basic form having two halves of an axle with a bevel gear on each end, connected together by a third Bevel gear forming up three sides of a square shape. This is usually supported by a fourth bevel gear for adding strength, completing the square shape. This basic unit is then connected by a ring gear and then attached to the differential case that carries another gear.

Open differential allows for completely different wheel speeds on the same axle, means no wheel slip will happen while turning around a corner, as the outside wheel will move further. From an efficiency point of view, less energy will be lost in differential as compare to alternate options.

Open differential is used in most of the commercial vehicles, which are run in normal tracks. Open differential provides 50%-50% torque both the wheels.

2.3 LOCKED DIFFERENTIAL

A locked differential is designed to get the better of the limitations of open differential by "locking" both wheels on an axle in conjugation or on a common shaft.

We can lock or unlocked the locked differential in dynamics as per our requirement. If its lock then it acts as a spool differential, & if it unlocks then its acts as an open differential. A locker unlocks with a certain amount of turning force, if it's an auto locker. Or selected when if it's some kind of manual locker.

Locked differential allows the torque to go to the wheel with the greater traction. Compared to all differential types, this will permit for the most torque to get to the track in any surface conditions. For off-road vehicle use where tire wear is not a problem, this regarding as absolutely it gets. Strong, simple, and very operative. In conditions where it's advisable to keep wheel speed constant on an axle, this is an effictive & easy solution.

Locked differential provides 100%-100% torque both the wheels in lock condition, and 50%-50% torque in unlock condition.

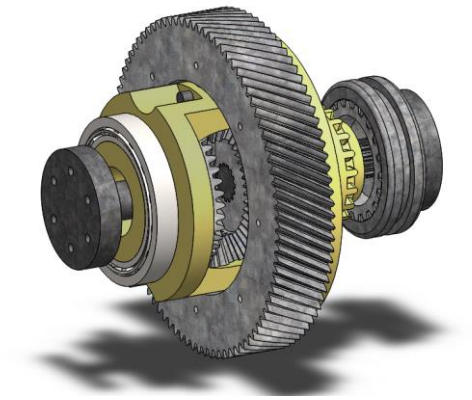

Fig -3: Locked Differential

Table -3: Locked Differentiable Specifications

Rotation of both wheels independently	PARTIALLY
Working at traction condition	YES
Adjustable biasing ratio	NO
Amount of Torque transmitted to wheel	100%-100%/ 50%-50%

2.4 LIMITED SLIP DIFFERENTIAL

A limited-slip differential is a type of differential that permits its two output shafts to rotate at different speeds. In race vehicles, such limited-slip differentials are used in place of open differential, where they give certain dynamic advantages, at the amount of greater complexity. Both open differentials & limited-slip differentials have a gear train that permits the output shafts to rotate at different speeds, while the summation of their speeds is proportional to that of the input shaft. Racing vehicle limited-slip differentials have some special type of mechanism that provides a torque that opposes the relative motion of the output shafts.

Limited slip differential allows different wheel speeds, thus reducing tire wear compare to locked differential. provides torque to the wheel which has more traction. Very smooth operating, provides good performance in a sharp turn too.

Limited slip differential basically classified in two types:

1. Clutch type limited slip differential
2. Gear type limited slip differential

2.4.(a) CLUTCH TYPE LIMITED SLIP DIFFERENTIAL

The clutch type limited slip differential basically consists of an open differential combined with clutch plates which can engage the side bevel gears to the differential case. As greater the torque, greater the locking effect. The clutch plates have a spline connection with the side bevel gears. The end plates are connected with the differential case by sliding contact. The end plates rotate at same speed as the differential case, and the clutch plates has same speed as the drive shafts side bevel gears.

Clutch type limited slip differential come in a wide range. 1-way, 1.5-way, 2-way. As per Application, they all works very similarly, with clutch pack that lock the differential, allowing for torque to be sent to the most grip traction wheel.

The disadvantage of clutch type limited slip differential is it require regular oil change, and the clutches get wear out due to continuous engagement and disengagement, so have to replace after certain cycles.

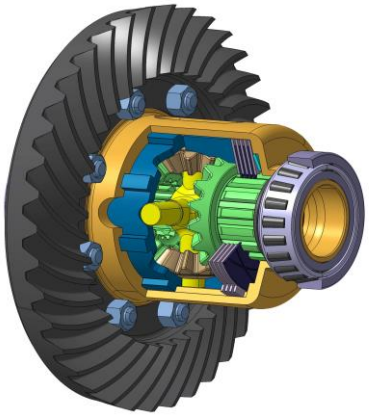

Fig -4: Clutch type Limited Slip Differential

Table -4: Clutch type Limited Slip Differentiable Specifications

Rotation of both wheels independently	YES
Working at traction condition	YES
Adjustable biasing ratio	YES
Amount of Torque transmitted to wheel	MANUALLY

2.4.(b) GEAR TYPE LIMITED SLIP DIFFERENTIAL

Gear type limited slip differentials are possibly the most common type of differential due to their huge range of applications. They work by transferring a torque to the wheel with greater traction, while limiting the slip of the wheel with less traction. Due to this, limited slip differentials are frequently mention as "torque sensing differential".

Same as open differential, the wheels are rotate at different speeds. Although, in a limited slip differential, every time torque is not steady between the wheels. This permits the wheel with traction to get more torque so as to continue to move the vehicle. Particularly, the differential is said to "Bias" more torque to the tire with higher traction. The total torque dissimilarity, the differential can move between wheels is mention as the bias of the differential.

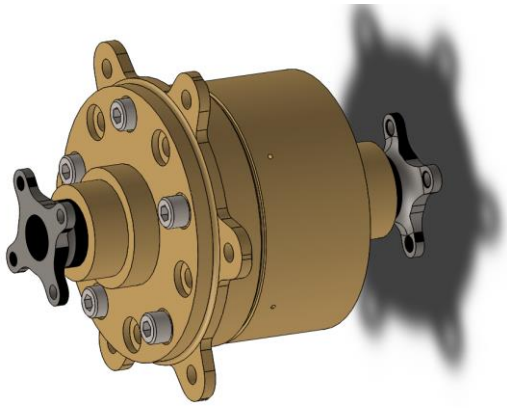

Fig -5: Gear type Limited Slip Differential

Table -5: Gear type Limited Slip Differentiable Specifications

Rotation of both wheels independently	YES
Working at traction condition	YES
Adjustable biasing ratio	YES
Amount of Torque transmitted to wheel	MANUALLY

From all study we decided to design and analysis the Gear type limited slip differential for our Formula Student Vehicle.

3. DESIGN AND ANALYSIS OF GEAR TYPE LIMITED SLIP DIFFERENTIAL

Following are the components that we have to design and analysis of gear type limited slip differential.

1. Differential head
2. Differential head slit
3. Differential base
4. Differential base slit
5. Sun gear
6. Planetary gears
7. Spring pack

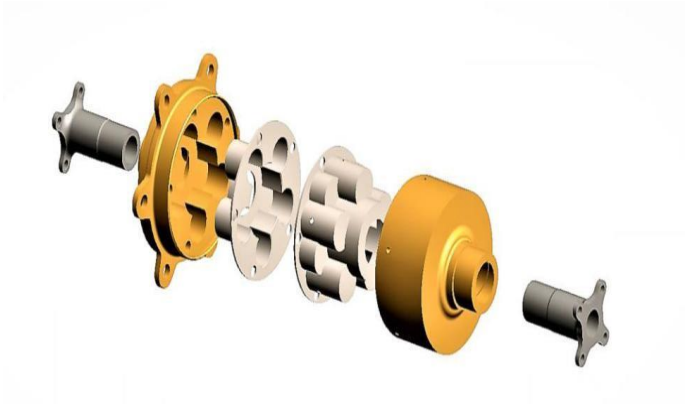

Fig -6: Gear type Limited Slip Differential

3.1 DIFFERENTIAL HEAD

Differential head is the upper outer half case of gear type limited slip differential. Having the housing of 5 planetary gears. Also, on differential head there is 6 bolting points for sprocket mounting. The material of differential head is Al7075 having lightest weight and high stress carrying capacity.

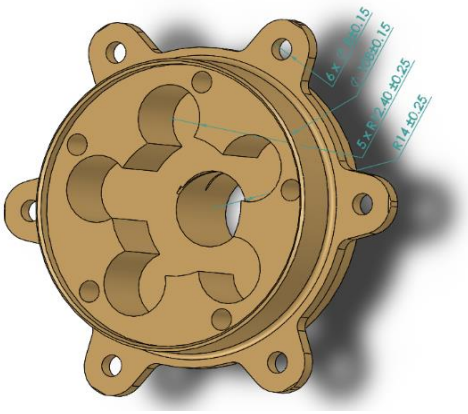

Fig -7: Differential Head

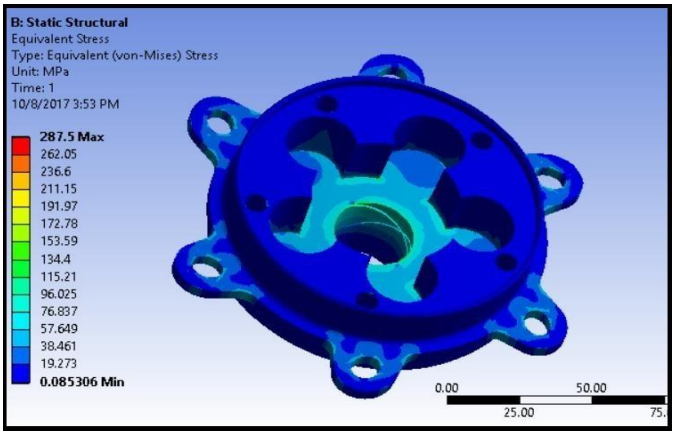

Fig -8: Differential Head Equivalent Stress

Table -6: FEA Results

Description	Maximum Stress (MPa)	Maximum Deformation(mm)	Meshing
Differential head	287.5	0.038	Triangular

3.2 DIFFERENTIAL HEAD SLIT

Differential head slit is the inner half covering of differential head of gear type limited slip differential. The inner planetary gears of differential are made up of steel material. When steel planetary gears are rotate inside the Al7075 casing, then there are chances to get wear out aluminum material from differential head. For that we design En19 slit having 2 mm thickness, which place inside the differential head which prevents the differential head from wear out.

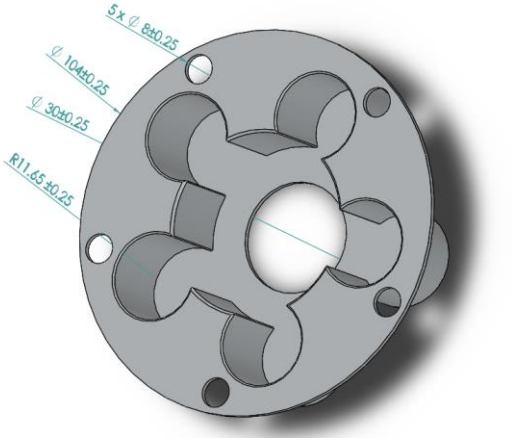

Fig -9: Differential Head Slit

3.3 DIFFERENTIAL BASE

Differential base is the lower outer half case of gear type limited slip differential. Having the housing of 5 planetary gears. Also, on differential base there is 5 bolting points through which differential head & base get bolted. The material of differential head is Al7075 having lightest weight and high stress carrying capacity.

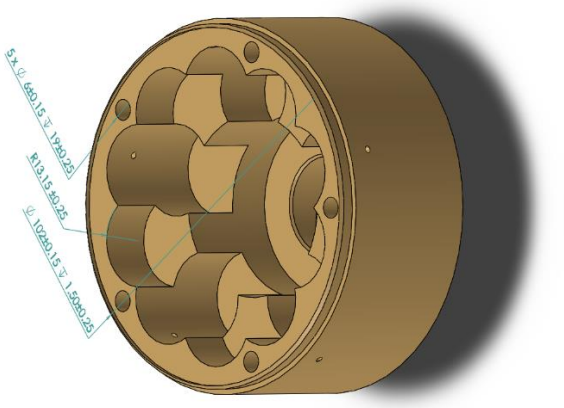

Fig -10: Differential Base

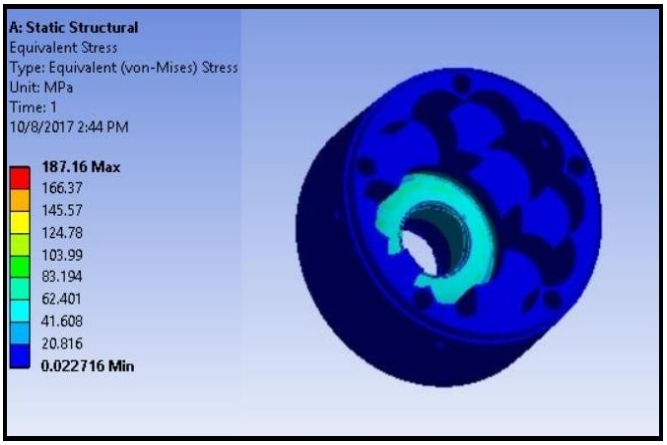

Fig -11: Differential Base Equivalent Stress

Table -7: FEA Results

Description	Maximum Stress (MPa)	Maximum Deformation(mm)	Meshing
Differential Base	187.16	0.035	Triangular

3.4 DIFFERENTIAL BASE SLIT

Differential base slit is the inner half covering of differential base of gear type limited slip differential. In differential base slit housing the planetary gears get mesh with each other. The material for differential base slit is En19 having 2 mm thickness.

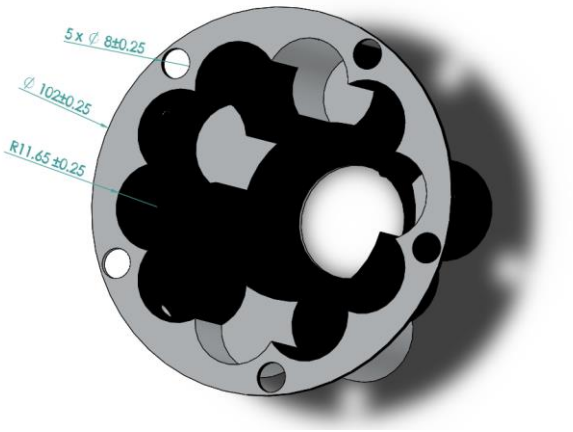

Fig -12: Differential Base Slit

3.5 SUN GEAR

There are two sun gears in gear type limited slip differential, that give an output torque from the differential to the tires with the of axles of the vehicle. Sun gear have a helical gear tooth profile and both are symmetrical to each other

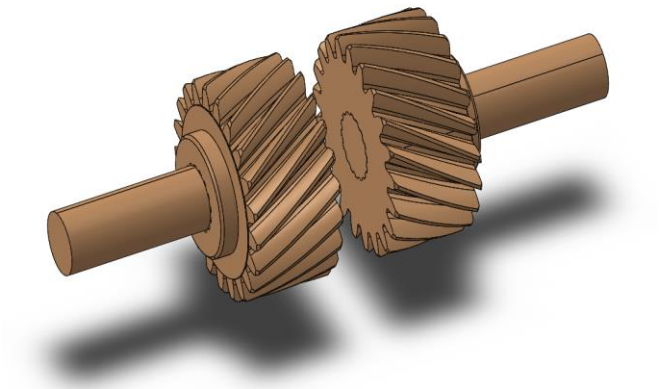

Fig -13: Sun Gears

3.6 PLANETARY GEAR

The planetary gear is the rotating component inside the differential, which helps both wheels to rotate at different speed. The planetary gear placed inside the differential head & base housing, which further mesh with two sun gears. There is total 10 number of planetary gears in our differential, having 5 gears on each head and base. Planetary gears have a helical gear tooth profile and each are symmetrical to each other**.** The material of planetary gear is Steel.

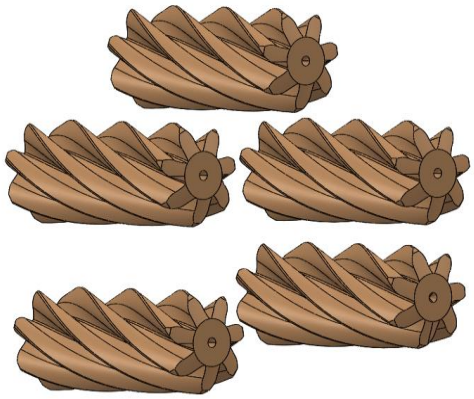

Fig -14: Planetary Gear

3.7 SPRING PACK

The spring pack, place in the center of the case of differential between the two sun gears. The components of the spring pack are

1. Star Cup
2. Two externally splined gears that fitted inside the star cup
3. Six Bellville washers

The star cup holds the two externally splined gears. In these gears the washers are mounted to apply an axial force. Since the gears are splined to the star cup, it can be observed that the Bellville washers are not permit to slide or rotate on each other.

The stiffness of the spring pack lies in the direction of the six Bellville washers and is directly proportional to the total torque required to break the internal friction of the differential. The orientation of the Bellville washers three times from left to right in alternate cup-to-cone.

Fig -15: Spring Pack

We select, design & analysis the gear type limited slip differential. Maximum stress is within permissible limit. Our design is safe.

4. CONCLUSION

We select, design & analysis the various type of differentials for a Formula Student race vehicle. We compare different types of differentials. And selected gear type limited slip differential, which fulfill our all requirements which is needed to formula student vehicles for finer torque transmission by differential, without accommodating reliability of vehicle.

ACKNOWLEDGEMENT

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BIOGRAPHIES

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