Design and Analysis of a 4 Wheel Drive Transmission for BAJA SAE

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Abstract - *An all-terrain vehicle (ATV) is engineered to navigate various surfaces and terrains, specifically designed to tackle challenging road conditions. Essential features of an ATV include high ground clearance and flexible suspension springs. The demand for a four-wheel-drive (4WD) transmission in lightweight ATVs is notably high due to its ability to enhance traction and augment off-road capabilities by distributing power across all four tires. This paper outlines a methodology focused on crafting and verifying a four-wheel driveline for a lightweight ATV, employing diverse modeling and simulation software tools. The integration of a Briggs and Stratton engine with a continuously variable transmission (CVT) allows seamless, infinite gear ratios within its predetermined range, ensuring smooth shifts. A two-stage reduction gearbox is utilized to amplify torque from the CVT, enhancing tire traction. Propelling power is transferred to the front differential through a propeller shaft, while a shifting mechanism facilitates the transition between two-wheel-drive (2WD) and 4WD modes. Detailed component designs are created using SolidWorks for iterative parameter adjustments. Additionally, the durability and material selection of driveline components are analyzed using Ansys software. The primary objective of this research paper is to establish a groundwork for future advancements in lightweight ATV driveline technology.*

Key Words: All-terrain vehicle, Off-road, Four-wheel drive, CVT, Gearbox

1.INTRODUCTION

The heart of a power transmission system, a transmission ensures precise power delivery. In the realm of BAJA SAE[1], this system comprises the engine, gearbox, driveshaft, differential, and axles. Its core function lies in transforming higher engine speeds into slower wheel rotations, augmenting torque in the process.

Gearboxes are intricate assemblies of gears varying in size, tailored to meet specific torque demands dictated by road conditions, load factors, and terrains.

BAJA SAEINDIA stands as an intercollegiate engineering design competition aimed at undergraduate and graduate students in engineering disciplines. It mirrors real-world engineering challenges, demanding teams to conceive, engineer, construct, test, advocate, and compete with a vehicle, vying for acceptance by a fictitious manufacturing firm. This multifaceted challenge necessitates teamwork, financial management, and a delicate balance with academic commitments.

2. METHODOLOGY

Considering all Baja competition events, the gearbox design prioritizes two crucial aspects: minimizing gearbox weight and ensuring the resilience of gear teeth. This approach unfolds in a systematic manner: Gear Ratio Calculation → Gear Design → Load Assessment on Gears → Material Selection for Gears → Gear Analysis → Determination of Factors crucial to Gear Performance.

2.1 Transmission Specifications

I. Engine (according to BAJA2021 Rulebook) [1]:

Engine: 19L232-0054-G1 (Briggs and Stratton).

Power: 10HP = 7.46 kW

Engine Torque (Te): 19.67 Nm.

Speed in rpm (N): 3800 rpm.

II. CVT: Customised JITRC1 [4]. CVT Ratio: 0.6 to 3.9

III. Diameter of Wheels: 0.558 m / 22 inch.

IV. Vehicle's Curb Weight: 220 kg.

V. Rolling Resistance (μ): 0.08

It varies based on road types and wheel design, with 0.08 being the universal maximum threshold.

VI. Transmission Efficiency (E): 75% (assumed, factoring in all losses).

3. GEAR SYSTEM CALCULATIONS

Maximum speed of vehicle is 60 Km/Hr as per the SAE BAJA 2021[1]. Based on a maximum torque of 500 Nm, our calculations suggest an optimal Gear Ratio of 8:1 for the two-stage Gearbox.

$$Max\ Speed\ of\ Vehicles = \frac{N \times C \times E \times 3.6}{CR \times GR \times 60}$$

CR is CVT Ratio, GR is Gear Ratio, E is efficiency of transmission, C is circumference of wheels.

$$60 = \frac{3800 \times 3.14 \times 0.558 \times 0.75 \times 3.6}{0.6 \times GR \times 60}$$

So, GR is 8.32
$Torque\ on\ wheels = Te \times CR \times GR \times E$
$500 = 19.67 \times 3.9 \times GR \times 0.75$

So, GR is 8.690

To achieve high speed, a low gear ratio is necessary, while higher torque demands a higher gear ratio. Given the vehicle's speed limit of 60 km/hr[1], we determined an optimal gear ratio of 8:1 for peak performance in balancing speed and torque.
Gear type is Spur Gear, with gear ratio of 8:1 and the gearbox type is a 2 stage compound gearbox.

Table -1: Gear Values at different stages

First Stage	Pinion=21 Gear=67 Face width=20 mm Module=2	Gear Ratio=3.2
Second Stage	Pinion=30 Gear=7 Face width=25 mm Module=2.5	Gear Ratio=2.5
Bevels at Gearbox	Pinion=20 Gear=24 Face width=30 mm Module=3	Gear Ratio=1.2
Differential Pinion	Teeth=22 Face width=45 Module=3	Gear Ratio=2
Differential Crown	Teeth=44 Face width=45 Module=3	Gear Ratio=2

$$First\ Stage\ Reduction = \frac{Number\ of\ teeth\ on\ gear}{Number\ of\ teeth\ on\ pinion}$$

$$= \frac{67}{21} = 3.2$$

$$Second\ Stage\ Reduction = \frac{Number\ of\ teeth\ on\ gear}{Number\ of\ teeth\ on\ pinion}$$

$$= \frac{75}{30} = 2.5$$

$$Total\ Reduction = First\ Stage \times Second\ Stage = 8$$

Reduction at Sun and Planet is taken as 1:1.

Table -2: Final Gearbox Values

Type of Gearbox	2 Stage Gearbox
Type of Gear	Spur Gear
Gear Ratio	8:1
First Stage Reduction Ratio	3.2
Second Stage Reduction Ratio	2.5
Pressure angle (β)	20

4. DESIGN OF GEARS

$$Pitch\ Circle\ Diameter\ (PCD) = Tn \times M$$

Here, Tn represents the number of gear teeth, while M signifies the module.

For Stage 1,
$PCD = 67 \times 2 = 134\ mm$

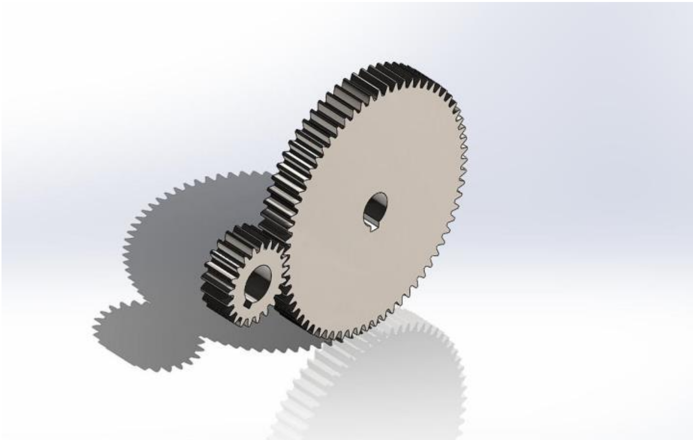

Fig -1: First Stage

For Stage 2,
$PCD = 75 \times 2.5 = 187.5\ mm$

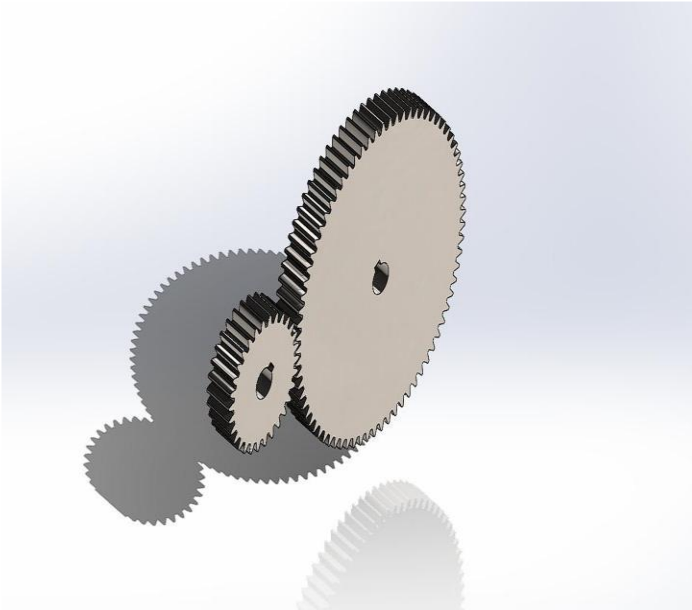

Fig -2: Second Stage

PCD for Bevel at Gearbox,
$PCD = 24 \times 3 = 72\ mm$

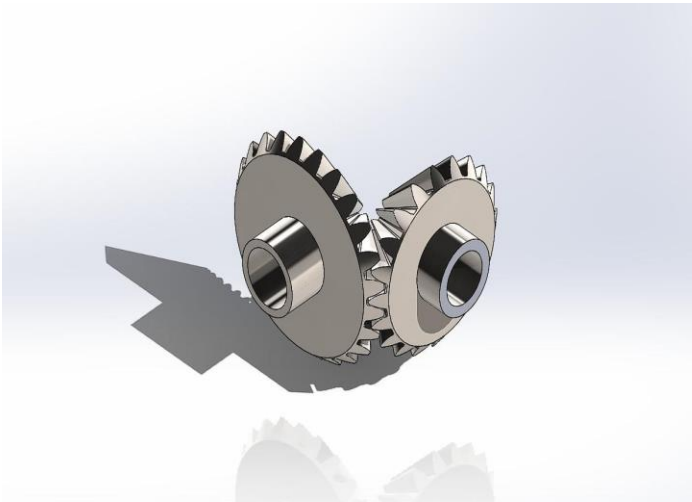

Fig -3: Bevel at Gearbox

For Differential Crown,
$PCD = 44 \times 3 = 132\ mm$

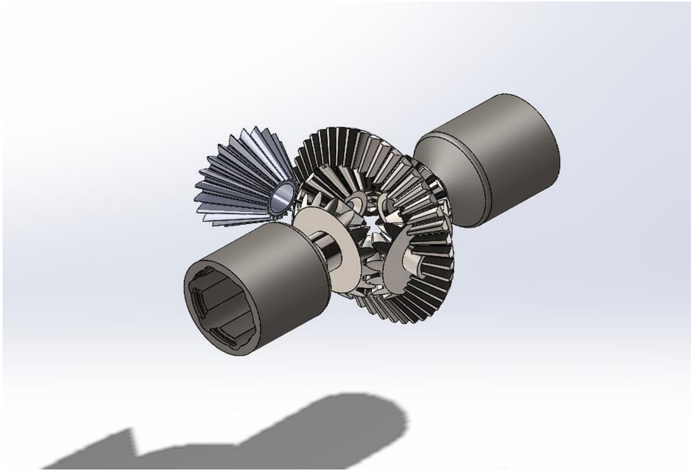

Fig -4: Differential Crown

5. CALCULATION OF LOADS ACTING ON GEARS

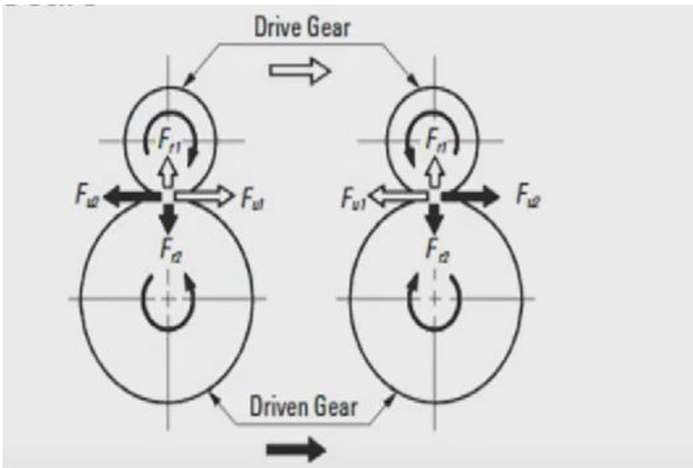

Fig -5: Forces Acting on Gears

For First Stage Gear,

(1) $$Tangential\ Forces\ (Ft) = \frac{2000 \times T}{PCD}$$

T is maximum torque, which is calculated as $19.67 \times 3.9 = 76.71\ NM$.

$$Ft = \frac{2000 \times 76.71}{134} = 1144.92\ N$$

(2) $Radial\ Forces\ (Fr) = Ft \times \tan(\beta)$
$= 1144.92 \times \tan(20) = 412.17\ N$

For Second Stage Gear,

(1) $$Tangential\ Forces\ (Ft) = \frac{2000 \times T}{PCD}$$

T is maximum torque, which is calculated as
$19.67 \times 3.9 = 76.71\ NM$.

$$Ft = \frac{2000 \times 76.71}{187.5} = 818.24\ N$$

(2) $Radial\ Forces\ (Fr) = Ft \times \tan(\beta)$
$= 818.24 \times \tan(20) = 294.56\ N$

Force of Bevel at Gearbox,

(1) $$Tangential\ Force\ (Ft) = \frac{2000 \times T}{Dm}$$

Where, Dm is the center reference diameter which is calculated as,
$Dm = d - (b \times \sin(\delta))$
b is Face width, $(\delta)$is cone angle
$(\delta) = \tan^{-1}(\frac{z1}{z2})$
z1 is number of teeth on pinion, z2 is number of teeth on Gear.
$= \tan^{-1}\left(\frac{20}{24}\right) = 39.7°$

$$Dm = 72 - (30 \times \sin(39.7)) = 53.1mm$$
$$Ft = \frac{2000 \times 76.71}{53.1} = 2894.71\ N$$

(2) $Radial\ Force\ (Fr) = Ft \times \tan(\beta) \times \cos(\delta)$
$= 2894.71 \times \tan(20) \times \cos(39.7) = 792\ N$

(3) $Axial\ Force\ (Fx) = Ft \times \tan(\beta) \times \sin(\delta)$
$= 2894.71 \times \tan(20) \times \sin(39.7) = 656.52\ N$

For Differential Crown,

(1) $$Tangential\ Forces\ (Ft) = \frac{2000 \times T}{PCD}$$

T is the maximum torque, which is calculated as $19.67 \times 3.9 = 76.71\ NM$

$$Ft = \frac{2000 \times 76.71}{132} = 1162.27\ N$$

(2) $Radial\ Force\ (Fr) = Ft \times \tan(\beta)$
$= 1162.27 \times \tan(20) = 418.41\ N$

6. GEAR MATERIAL SELECTIONS

Gear materials are selected based on loads acting on the gears in the endurance phase of the competition. The material should be low in cost and should be able to handle the maximum force acting. Gears should have a life expectancy of working through a complete season. Since the competition focuses on compactness and lesser weight of the ATV, the complete gearbox and differential should be compact and have as low weight as possible.

Table -3: Material Properties

	Gear Material	Gearbox Case Material
Material	EN19	AI 7075
Tensile Strength	655 MPA	572 MPA
Yield Strength	415 MPA	476 MPA
Young's Modulus	210 GPA	71.7 GPA
Poisson's Ratio	0.3	0.33

7. ANALYSIS OF GEARS

The analysis was conducted using ANSYS Workbench 19.2.

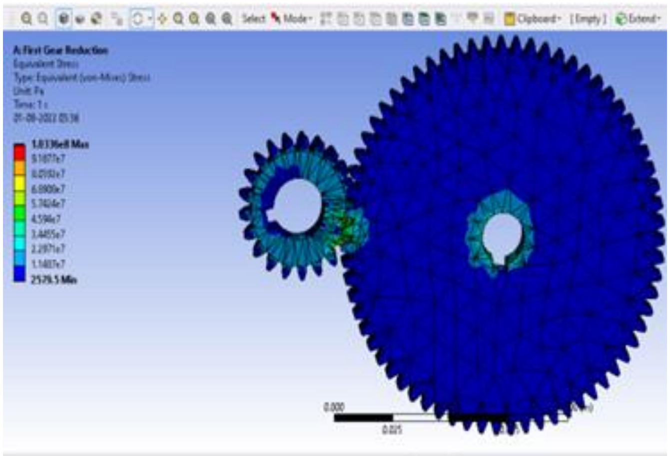

Fig -6: Stress Analysis of First Stage Gears

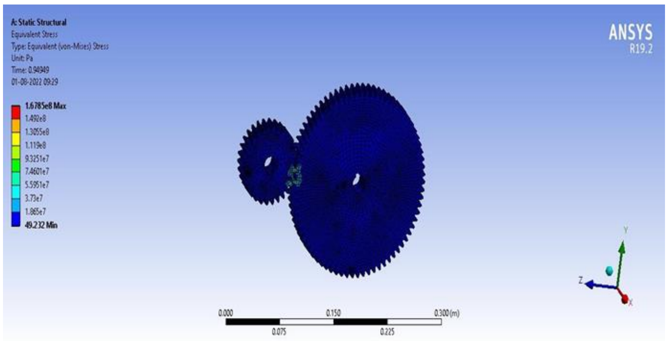

Fig -7: Stress Analysis of Second Stage Gears

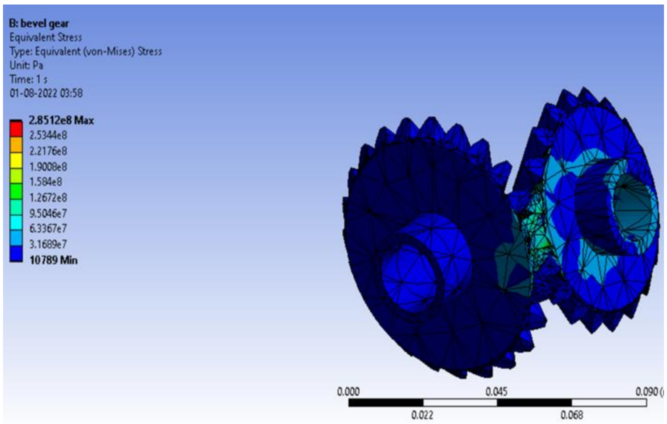

Fig -8: Stress Analysis of Bevel Gears

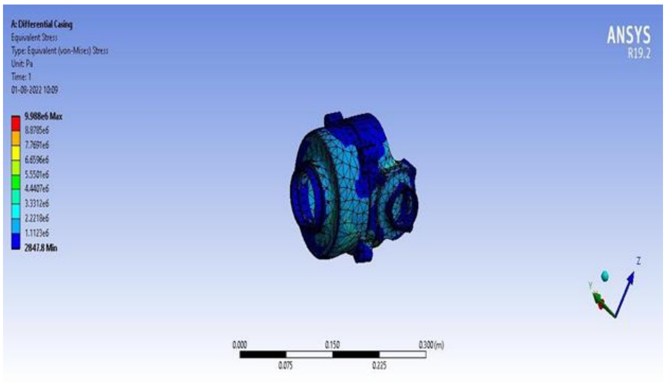

Fig -9: Stress Analysis of Differential Casing

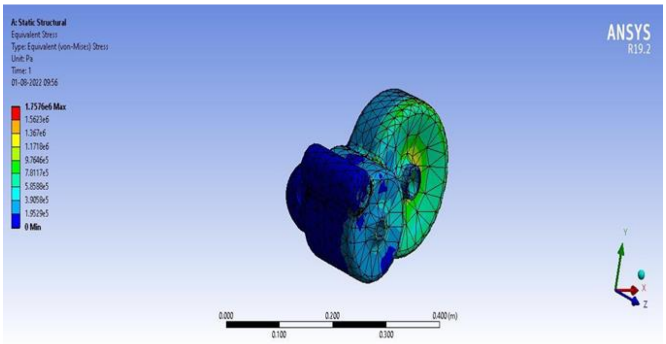

Fig -10: Stress Analysis of Gearbox Casing

8. CALCULATION OF FACTORS DEPENDING UPON THE GEARS

1. $$Max\ Speed\ of\ Vehicles = \frac{N \times C \times E \times 3.6}{CR \times GR \times 60}$$

$$= \frac{3800 \times 3.14 \times 0.558 \times 0.75 \times 3.6}{0.6 \times 8 \times 60} = 62.41\ \frac{Km}{Hr}$$

2. Acceleration

Tractive effort: Tractive effort refers to the force exerted at the driving wheel rims of a vehicle in motion, crucial for horizontal acceleration of the vehicle's mass[7].

$$Tractive\ Effort\ (TE) = \frac{Te \times CR \times GR \times E}{R}$$

$$= \frac{19.67 \times 3.9 \times 8 \times 0.75}{0.279} = 1649.74\ N$$

$$Rolling\ Resistence\ (RR) = W \times \mu$$
$$= 220 \times 9.81 \times 0.08 = 172.656\ N$$

$$Total\ Resistence(TR) = Air\ Resistence(AR) + Rolling\ Resistence\ (RR)$$

With the vehicle speed capped at 60 km/hr, negligible air resistance is anticipated.

$$TR = 0 + 172.656 = 172.656\ N$$

$$Acceleration = \frac{TE - TR}{m}$$

$$= \frac{1649.74 - 172.56}{220} = 6.71\ \frac{m}{s^2}$$

Gradeability: It refers to the capability of a vehicle to climb or ascend inclines or slopes while maintaining performance and speed.

$$Gradeability = \frac{100 \times (TE - TR)}{W}$$

$$= \frac{100 \times (1649.74 - 0.08)}{220 \times 9.81} = 68.44\ \%$$

3. $$Torque\ on\ wheels\ (TW) = T \times CR \times GR \times E$$
$$= 19.67 \times 3.9 \times 8 \times 0.75 = 460.278\ Nm$$

Where,
N: Engine Speed (rpm)
C: Wheel Circumference (m)
R: Wheel Radius (m)
W: Vehicle Weight (N)
m: Vehicle Mass (kg)
E: Transmission Efficiency (%)
CR: C.V.T Ratio
GR: Gear Ratio
T: Maximum Engine Torque (Nm)
Te: Engine Torque (Nm)
β: Pressure Angle

9. RESULT

After thorough design, analysis, and calculations, the following conclusions were drawn:

Table -4: Results

Material of Gears	EN19
Material of Gear Casing	AI 7075
Type of Gearbox	2 Stage Compound Gearbox
Overall Gear Reduction Ratio	8:1
First Stage Reduction Ratio	3.2
Second Stage Reduction Ratio	2.5
Differential Pinion and Crown Reduction Ratio	2
Bevels at Gearbox Reduction Ratio	1.2
Pressure Angle	20 Degree
No. of teeth in First Stage(Gear, Pinion)	67, 21
No. of teeth in Second Stage(Gear, Pinion)	75, 30
Max speed of vehicle	62.41 Km/Hr
Acceleration	6.71 m/s^2
Gradeability	68.44%
Torque on Wheels	460.278 Nm

10. CONCLUSION

The primary objective of this study was to meticulously design and analyze the transmission gearbox and differential for the SAE BAJA competition. This involved a comprehensive exploration of the forces impacting gears and gear reduction within the Machine Design course. Determination of overall gear ratios was crucial to achieving the desired speed and torque output.

Careful considerations such as gear material selection, teeth count, and gear type were made to mitigate potential failure risks. Detailed design analysis was conducted using ANSYS Workbench 19.0. Consequently, the transmission has undergone comprehensive optimization, ensuring its readiness to efficiently transmit the necessary speed and torque, enabling the vehicle to navigate all dynamic and endurance race obstacles in the SAE BAJA competition.

11. GALLERY

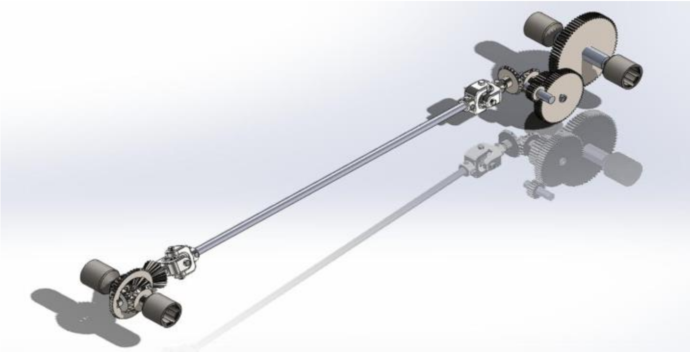

Fig -11: Complete Transmission Assembly

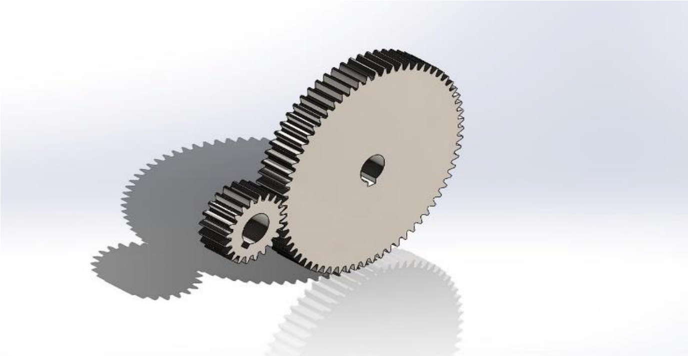

Fig -12: First Stage Reduction

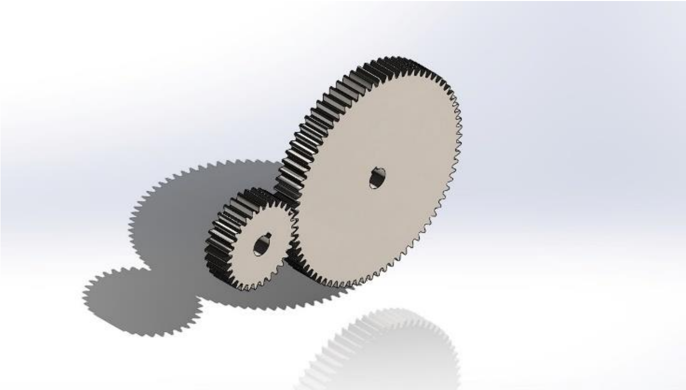

Fig -13: Second Stage Reduction

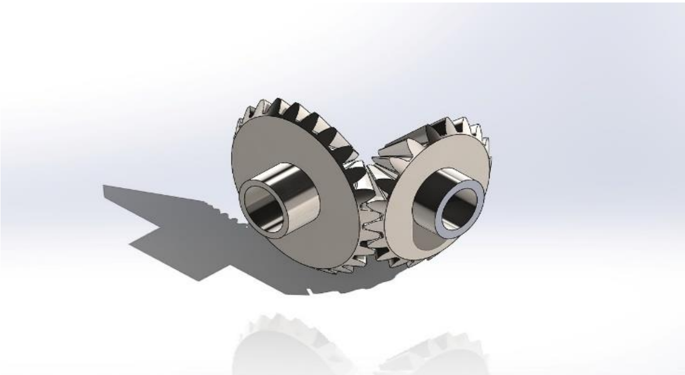

Fig -14: Bevels at Gearbox

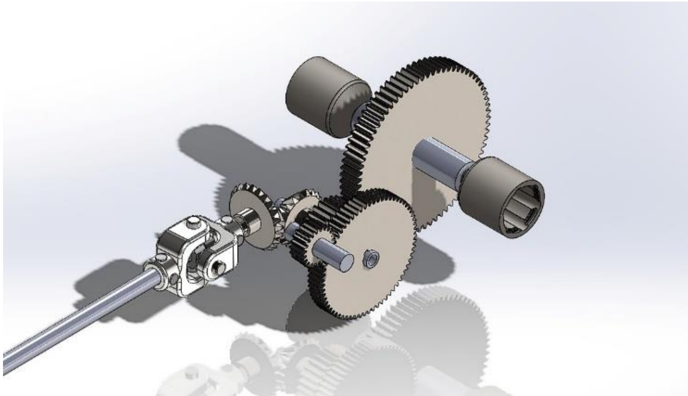

Fig -15: Gearbox Assembly

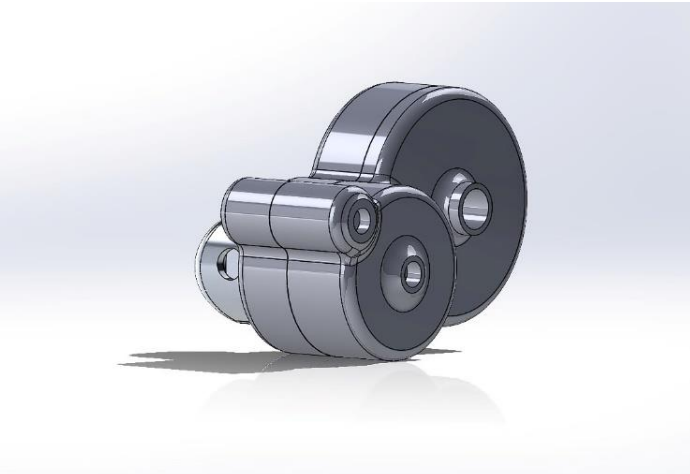

Fig -16: Gearbox Casing

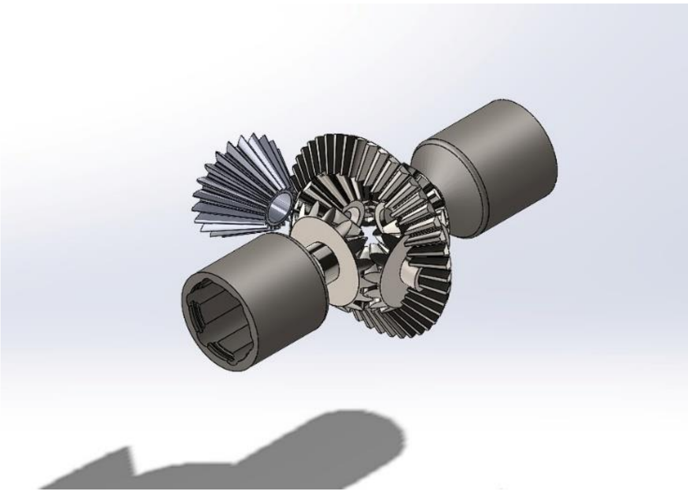

Fig -17: Differential Mechanism

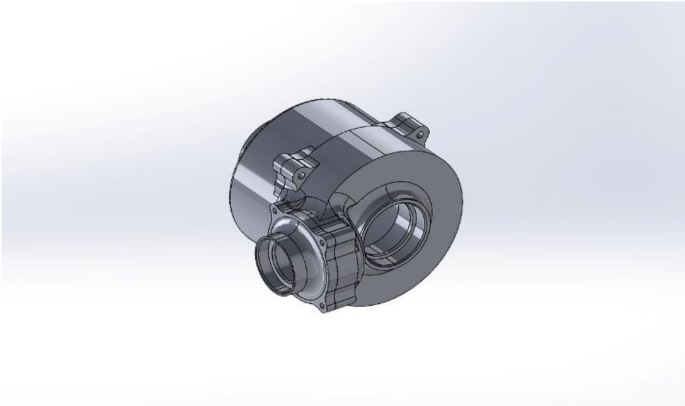

Fig -18: Differential Casing

REFERENCES

[1] SAE BAJA INDIA Rulebook 2021

[2] Machine Design by R.S.KHURMI AND J.K.GUPTA

[3] The 'Theory of Machines' by S. S. Rattan

[4] CVT Catalog: http://jitsolutions.co.in/product-cvt-1.html

[5] Boby George, Abin Jose, Adarsh John George, Ajay Augustine, Alvin Reji Thomas, 'Innovative Design and Development of Off-Road Vehicle Transmission System,' International Journal of Scientific & Engineering Research, Vol. 7, Issue 3, March 2016

[6] Dr. V.K. Sunil, Sunil Kumar, Abhishek Singh, Abhishek Srivastava, Amit Sharma, Prashant Dobriyal, 'Design And Development of an All-Terrain Vehicle Transmission System,' Volume 04, Issue 05, May 2017

[7] https://circuitglobe.com/tractive-effort.html

BIOGRAPHIES

"I am Ayub Ali Khan and I have done my graduation in BE in Manufacturing Processes and Automation Engineering from NSUT.
I am from Delhi, India and have a keen interest in Design and Computer Aided Engineering. "

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