

Design & Manufacturing of an Effective Steering System for a Formula Student Car

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Abstract- Steering system is used to direct the vehicle in the desired path. While maneuvering, the vehicle should steer in response to the driver's input command. The goal of this project is to design a good responsive steering system for high as well as low speed cornering for formula student car and retain the moderate cost, manufacturability, and low weight. The main consideration in design of the steering system is to produce pure rolling motion of the wheels while maneuvering the tightest corners. A safe design should be developed to ensure proper response to high speed cornering and heavy braking. It is essential to take human comfort and safety into consideration while designing. A steering system of lower steering ratio and weight as low as possible is designed, analysed and fabricated.

Index Terms- Turning radius, ergonomic, maneuver, ackerman, steering ratio

I. INTRODUCTION

The directional behavior of vehicle depends on the design of steering system. It is necessary to design a responsive steering mechanism which helps the driver in obtaining complete control on the maneuvering of the vehicle. Since the steering system is directly operated by the driver it is essential to take human comfort into consideration while designing the steering. The goal is to produce an optimal design to achieve higher strength to weight ratio. The purpose of the steering system is to direct the vehicle in the desired path. A purely mechanical rack and pinion mechanism is used for the vehicle. Steering ratio can be altered using different gear ratios for rack and pinion. An effective steering system should enhance the handling characteristics of the vehicle. A lower steering ratio is required for continuously changing the course throughout the race track. Steering effort and turning radius should lesser to

easily maneuver the vehicle along the tightest corner of the track.

II. DESIGN

A. Design Considerations

- The first step in designing the steering system is to determine the Wheelbase and Track Width of the vehicle. In accordance with formula student competition rules a minimum of 60 inches of wheelbase is required.
- Front track width should be greater than rear track width to ensure that while close
- to any obstacle or vehicle, the rear inner safely passes without dashing.
- The main aim is to obtain the turning radius as less as possible for maneuvering along a critical corner.
- For a steering system, selection of geometry is a major factor. Implementing proper geometry according to the cornering conditions is required.
- Considering the ease and cost of manufacturing, type of gear-pair and material is selected for rack and pinion.

B. Geometry Setup

There three types of steering geometries – Ackerman, Pro-Ackerman and Parallel steering. Parallel steering is not considered as an option as it causes the vehicle to understeer at a greater extent. As the formula student competitions require considerably lower speed cornering in dynamic events, for this purpose Ackerman Geometry is chosen. In Pro-Ackerman geometry, outer wheel steer angle being greater than inner wheel steer angle, the inner wheel gets dragged while cornering at lower speed and increase the steering effort.

For steering geometry design Dassault System Catia was used. It is better to use designing software than using analytical method. By putting various steering

parameters like minimum wheelbase, track width and other chassis parameters regarding the steering system a basic Ackerman geometry was obtained. In this we performed numerous iterations until we get the desired result.

In the geometry the rack was displaced to its maximum possible position as it would in an actual vehicle. At this displacement of rack the steering angle and turning radius of the vehicle was obtained through the geometry. After performing several iterations by analyzing the effects of varying the steering parameters such as length of tie-rod, rack, steering arm etc. a desired result was obtained providing the turning radius least of all the iterations and all following the Ackerman rule.

The final steering geometry is as follows:

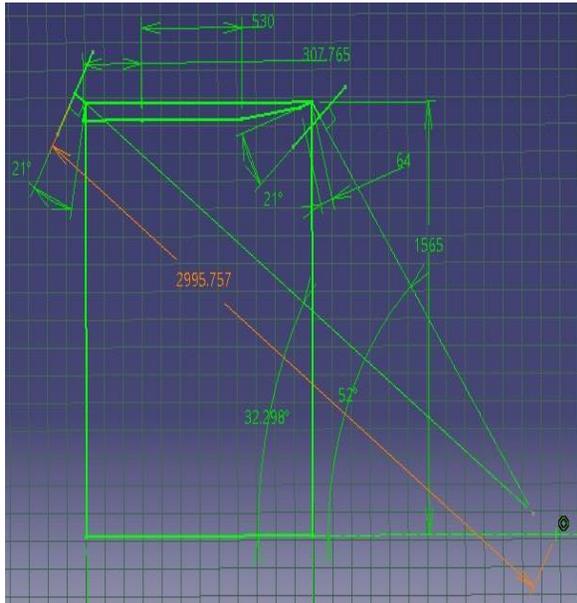


Fig. Ackerman Geometry

C. Geometry Validation

From the geometry,

Inner wheel steer angle (ϕ) = 52°

Outer wheel steer angle (θ) = 32.2°

Wheelbase (L) = 1565mm

Front Track Width (B) = 1325mm

Ackerman Condition,

$\text{Cot}(\theta) - \text{Cot}(\phi) = L/B$

By calculating, the Actual Ackerman condition obtained varies by around 5% from the Ideal Ackerman condition which is to be achieved. Hence the system is almost accurate.

D. Steering Specifications

Parameters	Values
Steering Ratio	2:1
Front Track Width	1325mm
Rear Track Width	1193mm
Rack Length	530mm
Rack Travel	70.972mm
Tie-Rods	307.7mm
Steering Arm	64mm
Steering Arm Angle	21°
Inner Steer Angle	52.01°
Outer Steer Angle	32.29°
Wheelbase	1565mm
Turning Radius	2997mm

Table No.1

E. Design of Rack and Pinion

Rack and pinion linkage was used for its ease of construction, manufacturability and better strength.

1) Gear Selection

For rack and pinion spur gear was chosen for its ease in designing and lesser manufacturing cost.

According to the BIS (Bureau of Indian Standard), 20°

Full Depth Involute gear profile was selected because of following advantages:

- Lesser risk of undercutting and interference
- Better load carrying capacity
- Better contact patch

2) Material Selection

Materials used in steering system should be lighter in weight and precise in operation. Also cost, manufacturability and reliability are important factors in material selection.

Light weight design and precise manufacturing are the main goals. If the manufacturing is not precise it can lead to ineffective steering mechanism.

From light weight point of view EN24, EN8, EN9 were not even considered. Light weight materials which can withstand the cornering and dynamic forces are Titanium, Carbon Fiber and Aluminium.

Considering the cost and manufacturability Aluminium Alloy 7075-T6 was used.

Property	Value
Density	2810 Kg/m ³
BHN	150
Ultimate tensile strength (S_{ut})	541 MPa

Yield strength (S_{yt})	503 MPa
Modulus of elasticity (E)	71.7 GPa
Poisson's ratio	0.33
Melting point temperature	477 °

3) Design of Gear-Pair

Design of Rack:

Number of teeth required for both side displacement of rack are 12.

To avoid clashing of teeth of pinion on the non-toothed part of the rack adding extra 5 teeth the rack.

Hence,

No. of teeth on rack are 22.

Design of Pinion:

Rack deflection wheel is turned through

$$52^\circ = 35.486\text{mm (Each side)}$$

Consider, $m = 2\text{mm}$

$$z^1 = d/m = \pi d/\pi m$$

πd (circumference of pinion) = rack travel

$$z^1 = 35.486/2\pi z^1 = 5.647$$

Considering, steering ratio as 2:1 i.e. when steering wheel is turned by 104° wheel will turn by 52°

For 104° of periphery of pinion no of teeth on pinion are 5.647 (6).

Teeth required for total rack travel are 12.

But the minimum number of teeth on a gear to avoid interference are 17.

Hence, $Z = 17$ mm

4) Beam Strength

When two gears are in mesh, the teeth of the gears act as a cantilever beam and a tangential load acts at the contact point of the two teeth. Beam strength is the tangential load capacity of the gear tooth.

Beam Strength,

$$F_b = m.b.Y.\sigma_t$$

$$b = 10m = 20 \text{ mm}$$

Y – Lewis form factor

For 20° full depth profile,

$$Y = 0.484 - 2.865/z$$

$$Y = 0.3332$$

$$\sigma_t = S_{ut}/3 = 176.67 \text{ MPa}$$

$$F_b = 10m^2 \times 176.67 \times 0.3332$$

$$F_b = 588.66m^2 \text{ N}$$

5) Wear Strength

Along with bending strength a gear tooth should be durable enough against pitting, crowing and wearing

of the teeth. Wear Strength determines the capacity of the gear tooth against tooth fatigue and tooth surface wear.

$$F_w = b.Q.d_p.K$$

$$Q\text{- Ratio factor} = (2Z_g) / (Z_g + Z_p)$$

$$K\text{- Hardness factor} = 0.45(\text{BHN}/100)^2$$

$$F_w = 236.67m^2 \text{ N}$$

6) Forces and Moments in Steering system

Forces and moments were calculated arising due to normal reaction at tire-road interface due to vertical load and aligning torque while steering the vehicle.

The driver must apply an effort on the steering wheel to overcome the aligning torque.

From suspension geometry following parameters were finalized which has a direct effect on steering response:



Fig. KPI

1. King pin inclination (λ) = 8°

2. Scrub radius (d) = 55mm

3. Caster Angle (ν) = 5°

4. Steer Angle (δ) = 52°

Mass of the vehicle with driver – 250kg

Considering the weight distribution of the vehicle 40:60.

Mass on the front axle is (250 x 0.4).

Hence, $F_z = 981 \text{ N}$

- Moment arising due to vertical load acting on the Front Wheels-

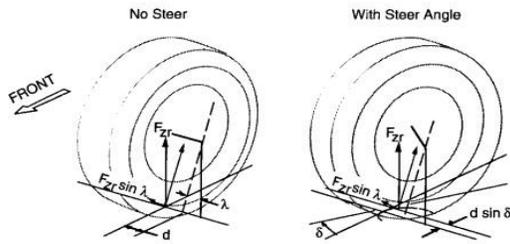


Fig. Moment due king pin inclination

$$M_V = (F_{ZR} + F_{ZL}). d. \sin \lambda. \sin \delta$$

F_Z – Vertical Load, N

Calculating the values of F_{ZR} and F_{ZL} considering the lateral load transfer while cornering.

$$M_V = 5917 \text{ N-mm}$$

- Moment arising due to caster angle-

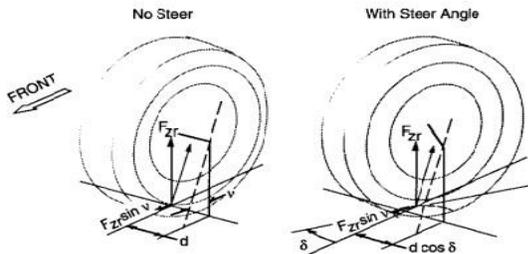


Fig. Moment due to caster angle

$$M_V = (F_{ZL} - F_{ZR}). d. \sin v. \cos \delta$$

$$M_V = 1412 \text{ N-mm}$$

$$\text{Total Vertical Moment, } M_{VT} = 7329 \text{ N}$$

- Aligning Torque-

$$M_{AT} = (M_{VL} + M_{VR}). \cos \sqrt{(5^2 + 8^2)}$$

$$M_{AT} = 14459.7 \text{ N-mm}$$

Total effective moment,

$$M = 21788.75 \text{ N-mm}$$

Tangential force across the pinion,

$$M = F_T \cdot \text{Steering Arm Length}$$

$$F_T = 340.49 \text{ N}$$

$$P_{eff} = K_a \cdot K_m \cdot P_t / K_v$$

P_t – tangential force on pinion

From design data book,

$$K_m = 1.3$$

$$K_v = 1$$

$$K_a = 1$$

$$P_{eff} = 443.63 \text{ N}$$

7) Estimation of Module

Gear pair is weaker in wear strength than in beam strength.

$$F_w = FOS \times P_{eff}$$

Consider, FOS-1.5

$$236.67 \text{ m}^2 = 1.5 \times 443.63$$

$$m = 1.68$$

Hence considering standard module,

$$m = 2 \text{ mm}$$

After the estimation of module, the other dimensions of gear pair are determined.

Pinion Dimensions:

Module of Pinion = 2mm

No. of teeth on pinion = 17

Pitch circle diameter = 34 mm

Width = 10 x m = 10 x 2 = 20 mm

Addendum = 1 x m = 2mm

Dedendum = 1.25 x m = 2.5 mm

Addendum circle = PCD + addendum = 38 mm

Dedendum circle = PCD – dedendum = 29 mm

Rack Dimensions:

Module = 2

No. of teeth on rack = 22

Diameter = 20 mm

Length = 530 mm

F. CAD Model of Rack and Pinion

As per the obtained dimensions, the rack and pinion were precisely designed on the CATIA software for manufacturing.

- CAD model of Pinion:

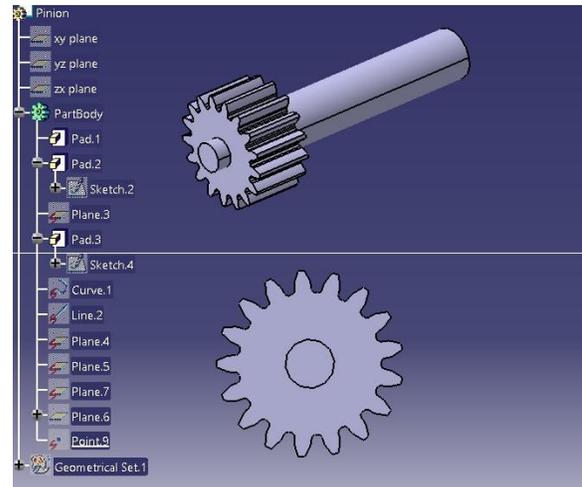


Fig. CAD Model of Pinion

• CAD Model of Rack:

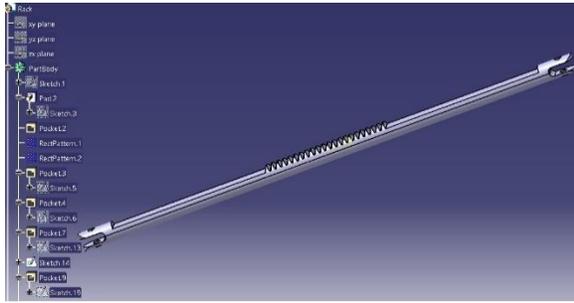


Fig. CAD Model of Rack

• CAD Model of Casing:

Delrin Polymer material was used for the casing of rack and pinion. Delrin is very light in weight, cheap and easy to machine. It hard enough to withstand the forces.

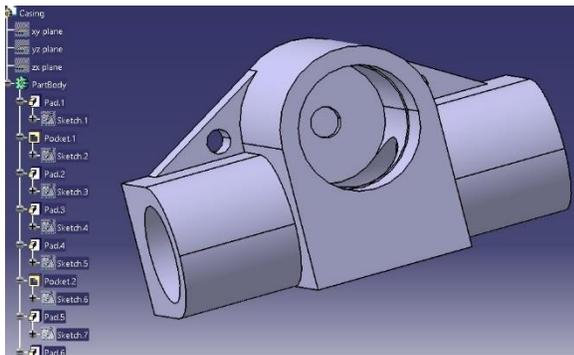


Fig. CAD Model of Casing

• CAD Model of Assembly:

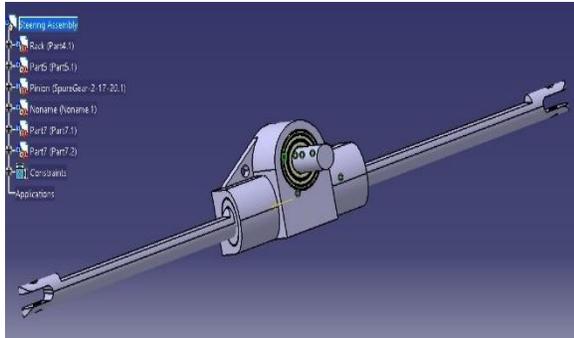


Fig. CAD Model of Rack & Pinion assembly

F. FEA of the system using ANSYS

For FEA of the system the rack and pinion assembly of the system was put under motion constraints and tangential load was applied to check for the tooth failure and bending of the rack.

Using the results obtained from the FEA, minor changes were made in CAD model.

FEA of Rack and Pinion:

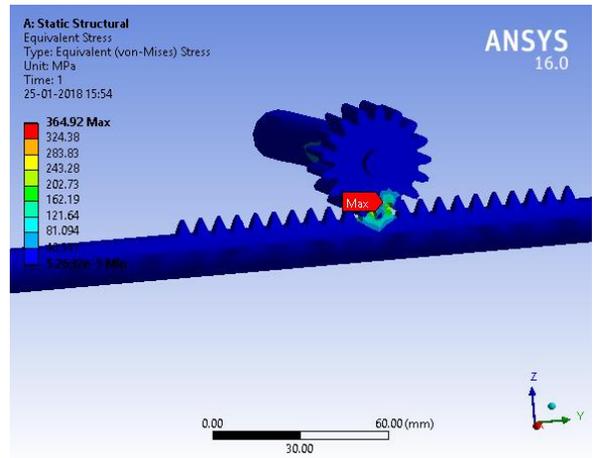


Fig. Equivalent Stress

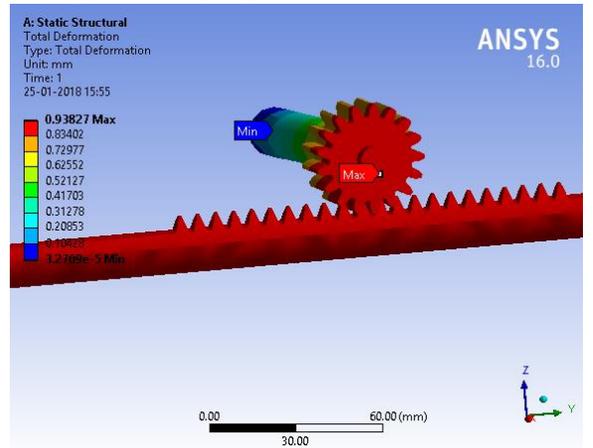


Fig. Total Deformation

Parameter	Result
Stress	365Mpa
Deformation	0.9mm
FOS	1.38

G. Manufactured Parts

Rack and Pinion was manufactured at a very cheaper using a Milling machine. Assembly casing was manufactured on a DRO machine.



Fig. Rack n Pinion



Fig. Polymer Casing

H. Steering effort calculation:

Tangential force on pinion = 443 N

Radius of pinion = 17mm

Torque on pinion = 7531 N-mm

Radius of steering wheel = 125mm

Force on steering wheel = 60.2 N

Thus, effort on Steering wheel is only 60.2N by one hand, which is within ergonomic consideration.

III. CONCLUSION

While designing any sub-assembly for the formula student vehicle, strength to weight ratio should always be maintained.

For rack and pinion, the casing should be precisely manufactured to exact center distance. Error microns can also affect the effectiveness of steering.

Steering effort should be adequate for the driver to easily maneuver through the corner.

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