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Design & Manufacturing of Steering System for FSAE Vehicle

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***Abstract* - The following article will help you in understanding about how a steering system is an FSAE vehicle is designed and manufactured considering all types of stresses, strains and other mechanical properties acting on it. The primary objective of the steering system is to enable the driver to continuously manoeuvre the path of the vehicle and provide a good steering response to the driver. This report focuses on the design, manufacturing and tuning of the steering system. The main focus was given on reducing the weight of the system along with reducing the free play at the steering wheel to ease the handling and increasing the stability at high speeds.**

Key words: - Steering System, FSAE, Objective, Manoeuvre

I. INTRODUCTION

A steering system is a system of a vehicle on which a driver gets the first feedback about the surface of the road. The steering system consists of components, linkages, etc. which allows a vehicle to follow the desired course. This system is used to steer the front wheels present in the vehicles in right or left direction. The steer is given with a component which is called the steering wheel. This steering wheel is positioned in front of the driver and is connect to the front wheels with a column, universal joints and gears. There are 2 types of steering geometry mainly in the industry today. First one is the Ackerman Steering Geometry and second one is the Anti-Ackerman Steering Geometry. In the FSAE vehicle we use the Anti-Ackerman Steering Geometry as it has more advantages for a race car over the other type of geometry.

II. DESIGN OBJECTIVES

1) Design a new system with eliminated bulky support and improvised ergonomics using a singleuniversal joint.
2) To introduce an adjustable steering geometry as required for different dynamic events.
3) To minimize the compliance in the system this will ease the handling and provide better stability at high speeds.
4) To optimize the weight of the system to less than 3 kgs.
5) Reducing the turning radius to 4m.

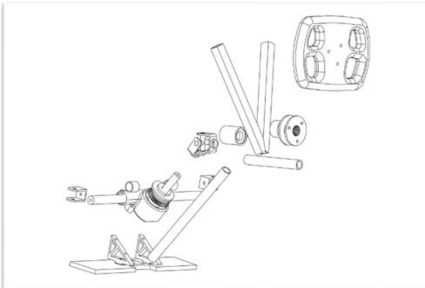

Figure 1: Steering system

III. DESIGN CONSIDERATIONS

Whilst designing any system, it is important to take into account various conditions the system will be exposed to. Steering is one of the two systems which takes input from the driver and transfers it to the tire. Following are the considerations made while designing the steering system.

- Coefficient of friction between road and tire = 1
- Weight of the car = 250 kgs
- Minimum radius of the track = 4.5 m

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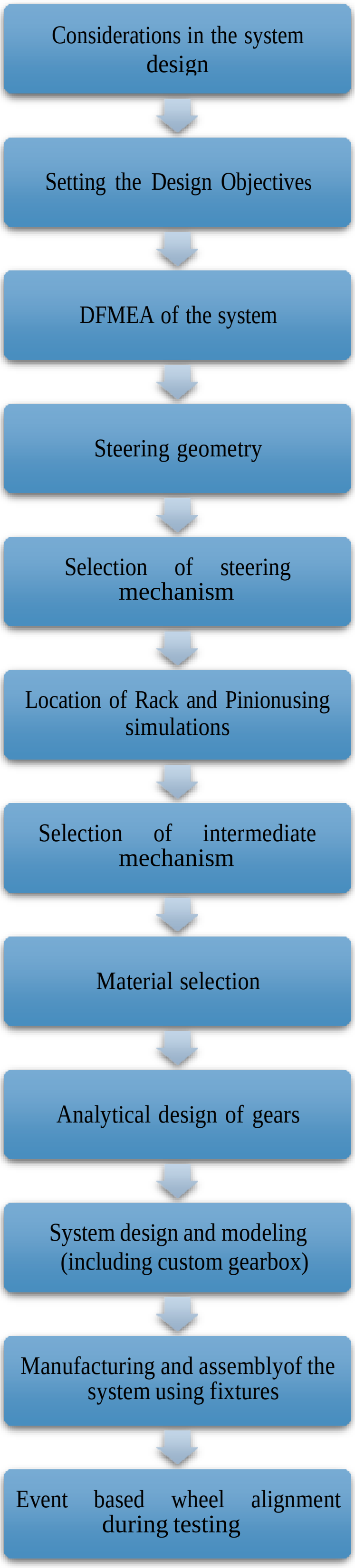
IV. DESIGN PROCEDURE



V. DFMEA

Failure Modes and Effects Analysis (FMEA) is a systematic, step by step failure analysis technique which evaluates the processes for possible failures and to prevent them by correcting the process ratherthan reacting to its effects after the failure.

Design Failure Modes and Effects Analysis (DFMEA) is first done by identifying all the components of the system. This is followed by identifying the failure mode for each component, its causes, effects on the system and the vehicle as a whole. After the above step, severity of the failure, likelihood of occurrence of failure and its detection is rated for each failure mode.

DFMEA of a system helps the designer to identify the most critical components of the system andmodify the design so as to reduce the risk of its failure.

Table 1: DFMEA of steering system.

Component	**Failure cause**	**Failure effect**	**Severity**	**Preventive measure**
Steering Wheel	Lesser torque applied during FEA	System Failure	10	Verification of Steering torque
Quick Release	Fatigue erosion	Increased free play	4	Hardening of splines
Friction bearing Universal Joint	No sustainable material used	Decreased stability at high speeds	6	Use of needle bearing UJ
Rack & Pinion	Improper Design	Increased effort and wear	7	Research on gear design
Rod - ends	Misaligned Line of Action	System Failure	10	Fixtures to be used in Manufacturing process
Steering Column	Excessive torque applied	Input required from driver increases	8	Validation of torque

VI. SELECTION PROCESS

i. Steering geometry and percentage

It is the geometric arrangement of linkages in the steering of a car or other vehicle designed to solve theproblem of wheels on the inside and outside of a turn needing to trace out circles of different radii.

Ackerman steering	**Anti-Ackermansteering**
No skidding at front tires	Leads to excessive skid
Less response to driverinputs	Very poor response
1.9° camber gain	0.9° camber gain
Better for skid pad	Better at high speeds

Table 2: Comparison of Steering Geometry

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a) Anti-Ackerman steering neither provides good response nor provides stability during cornering.

b) Ackerman steering is stable and thus better for skid pad but is a bit less responsive.

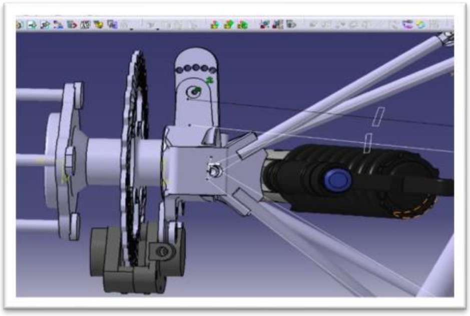

Figure 2: Mechanism to determine optimum Ackerman percentage.

Thus, it was necessary to find a trade-off between stability during cornering and responsiveness. For this,a mechanism was incorporated between the knuckles which would provide an experimental value for the steering geometry as per the events.
Based on testing results and driver feedback, following values were chosen:

Event	Ackerman Percentage
Skid pad	86
Autocross	37

Table 3: Finalized steering geometries

ii. Steering mechanism

The rotary motion of the steering wheel is transferred to the wheels of the car via a suitable mechanism. This mechanism takes input from the steering column and transfers it to the tie rods which are further connected to the wheels. This chooses mechanism

a. Must convert rotary motion into linear
b. Have a linear output
c. Sustain the steering torque

Rack and Pinion	Recirculating Ball
Fewer moving parts	More complex with moremoving parts
Less mechanicaladvantage	More mechanicaladvantages
Less wear if hardenedinitially	More parts result inincreased total wear
Requires less space and is lightweight	Requires less space but is too heavy

Table 4: Alternatives for steering mechanism

Thus, we can conclude that rack and pinion mechanism have many advantages over the other two except that of less mechanical advantage. This problem was solved by a discussion with the suspension and wheel assembly team. It was decided to increase the steering arm length to gain mechanical advantage over the uprights.
Accordingly, a custom rack and pinion was designed and manufactured.

Figure 3: Manufactured rack and pinion

iii. Location of rack and pinion

The two major factors deciding the position of rack and pinion are:

1. Inversion of the four bar mechanism
2. Packaging

Case 1: Steering rack behind the front axle.

This position would solve the problem of packaging the wheel assembly inboard. However, this resulted in early inversion of the linkages. It restricted the turning of the inner wheel to 28°. The outer wheel for 80% Ackerman would turn 21° giving a turning radius of 4.3m which is far away from desired.

Case 2: Steering rack ahead of front axle.

This pushed the point of inversion forward and the desired turning angles were achieved. Also, during cornering, the outer wheel handles more loads and the tie rod attached to this wheel will be under tension which is safer than it being under compression. The problem of packaging was solved by selecting rims with greater step offset as required.

iv. Selection of intermediate mechanism.

After prototyping of the chassis and the seating position of the driver, the angle of the steering wheelwas finalized as 20° with the vertical. This could be achieved with three mechanisms as:

Alternative for	Choice
Steering geometry	Ackerman (37% for autocross) (95% for skid pad)
Steering mechanism	Rack and pinion
Location of steering mechanism	Ahead of front axle
Intermediate mechanism	Single UJ

Table 5: Alternatives for intermediate mechanism.

Thus, with a discussion with the suspension team, the height of the gearbox was increased and a single UJ was selected by giving an inclination to the gearbox.

To summarize with, following selections were made:

Single UJ	Bevel gearbox
300 grams	900 grams
No additional supportstructure required	Additional support required
Increased height of rack andpinion	Less height of rack and pinion
High sensitivity at small turning angles as desired forautocross	No such desired effect

Table 6: Summary for selections amongst alternatives

VII. MATERIAL SELECTION

Selection of appropriate material considering the operating conditions, fatigue life, elasticity hardnessetc. decides the endurance limit of the component. Following were the considerations for componentstaken into account prior the selection of materials:

a. Steering wheel: Sustain the steering torque, provide adequate grip and be lightweight.
b. Quick release: Have high wear resistance.
c. Column and single UJ: Sustain Steering torque.
d. Rack and pinion gears: Must not fail against bending load on teeth and have a thigh BHN.
e. Gearbox casing: Rigid and lightweight.
f. Clevis: Serve the functionality.
g. Tie rods: Must not buckle under dynamic forces.

Following is a table consisting major components of the system, their materials and process used for its manufacturing.

Component	Material
Steering wheel	Composite (carbon fiber)
Quick Release	Mild steel (hardened)
Column	Mild steel
Single UJ	Steel
Rack and pinion gears	EN 19 (hardened)
Gearbox casing	Aluminum 6082
Clevis	Mild steel
Tie rods	Mild steel

Table 7: Material selection

VIII. CALCULATIONS

i. Turning radius:

As stated in the objectives, the desired turning radius is 4m which was decided considering that the leastturning radius of the track among all the dynamic events would be 4.5 m.

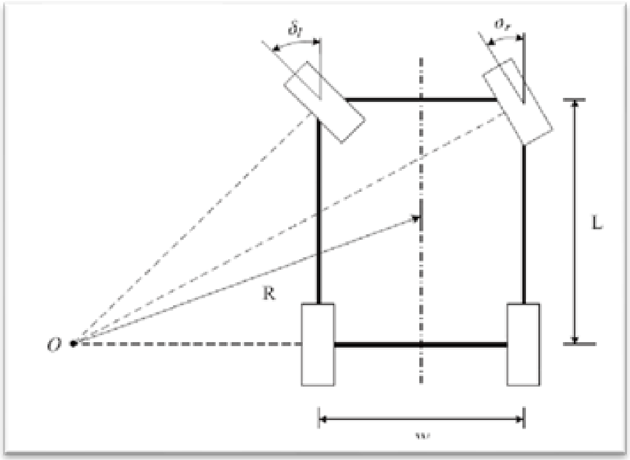

Figure 4: Turning radius

As seen above the turning radius of the vehicle is:

$$\text{Turning Radius} = \frac{\text{wheel base (L)}}{\boldsymbol{\delta r}}$$

$$4000 = \frac{1545}{\boldsymbol{\delta r}}$$

$$\boldsymbol{\delta r = 22.72°}$$

We have,

$$Ackerman = \tan^{-1}\left(\frac{Wheel\ Base\ (L)}{\frac{wheel\ base}{\tan(\delta r)} - track_{front}}\right)$$

$$\text{Ackerman \%} = \frac{\delta 1}{\text{Ackerman}} * 100$$

By solving δ1 at 95% we get,

$$\boldsymbol{\delta 1 = 27.24°}$$

In the Lotus software, a kinematic analysis was performed and the above angles were obtained at a racktravel of 39mm, eye to eye 380mm and a steering arm length of 60mm.

Accordingly, rack and pinion was designed for 39mm travel on either side or pinion lock to lock180º.

ii. Rack and pinion gear

- Rack travel (either side) = 39mm
- Pinion (either side) = 90º
- Module = 1.5mm

a) $Rack\ Travel = \frac{\pi D_{pinion}}{4}$

Dpinion = 49.65 mm

b) $Z_{pinion} = \frac{D_{pinion}}{m}$

Zpinion = 33

c) *Zrack = Zpinion*

Zrack = 33

d) *Tooth depth (h) = 2.25m*

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h = 3.375mm

e) *Addendum (ha) = 1.00m*

ha = 1.5mm

f) *Dedendum (hf) = 1.25m*

hf = 1.875mm

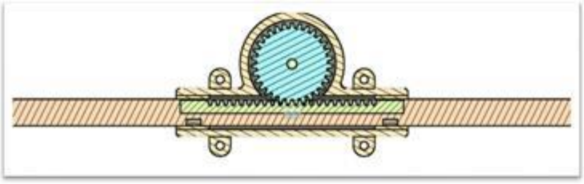

Figure 5: Sectional front view

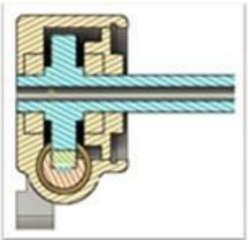

Figure 6: Sectional side view

iii. *Steering effort:*

Total mass of the car = 250 kgs

Load transfer during braking = 27.5 kgs

Maximum weight on front end = 0.45 ∗ 250 + 27.5

= 140 kgs

= 1373.5 N

Steering effort is the force applied at the steering wheel to produce a torque about the steering axisresulting in turning of the front wheels.

The weight on the front axle is equal to the net force transmitted by the rack to the tie rods.

∴ Net force in the rack (F_{rack}) = 1373.5 N

This force is generated by a torque in the pinion.

$$Torque_{pinion} = F_{rack} * Radius_{pinion}$$

$$Torque_{pinion} = 34.094\ Nm$$

This is the torque produced in the steering wheel by the driver.

The radius of steering wheel is 230 mm

$$F_{driver} = \frac{Torque_{pinion}}{Radius_{steering\ wheel}}$$

Fdriver = 148.23N = 15.11 kgs

iv. *Steering Ratio*

Steering ratio is defined as the ratio of angle turned by the steering wheel to that turned by the wheels of the car. Mathematically,

$$Steering\ Ratio = \frac{\theta_{steering\ wheel}}{\frac{\delta_r + \delta_l}{2}}$$

$$Steering\ ratio = 3.60$$

v. *C – Factor*

C-factor in steering is defined as rack travel per 360º rotation of pinion.

$$C - factor = \pi D_{pinion}$$

$$\mathbf{C - factor = 155.98\ mm}$$

IX. CONCLUSION

This is the way in which a steering system is to be designed and similarly manufactured for a FSAE vehicle. These calculations are made with respect to a car which is designed by us. Similar calculations can be done for other vehicles which are using different types of steering geometry and can be validated with the help of various software like ANSYS or LS - DYNA. This will give an idea that how good the system is designed

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