Design and Simulation of Manual Rack and Pinion Steering System

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Abstract- *Manual rack and pinion steering systems are commonly used due to their simplicity in construction and compactness. The main purpose of this paper is to design and manufacturemanual rack and pinion steering system according to the requirement of the vehicle for better manoeuvrability. Quantities like turning circle radius, steering ratio, steering effort, etc. are inter-dependent on each other and therefore there are different design consideration according to the type of vehicle. The comparison of resultis shown using tables which will help to design an effective steering for the vehicle. A virtual rack and pinion assembly can be created using software like SOLIDWORKS and ANSYS.*

Keywords- Steering ratio, steering wheel torque, inner wheel and outer wheel angle, Rack and Pinion steering.

I. INTRODUCTION

In this paper a virtual prototype of rack and pinion assembly with complete SOLIDWORKS geometry is proposed to enhance and facilitate steering response by varying the different parameters employed during its design and manufacturing. It is important to know how the different aspects like steering ratio, pinion diameter, rack length etc. govern the working of the mechanism. The possibility of decreasing lock to lock steering degree has motivated us to work upon this system.

According to Ackermann Steering geometry, the outer wheels moves faster than the inner wheels, therefore, the equation for correct steering is:

$$\text{Cot } \Phi - \text{Cot } \theta = {}^{b}/_{l}$$

In the image shown below,
Φ = outer wheel angle
θ = inner wheel angle
b = track width
L = wheelbase
α = Ackermann angle

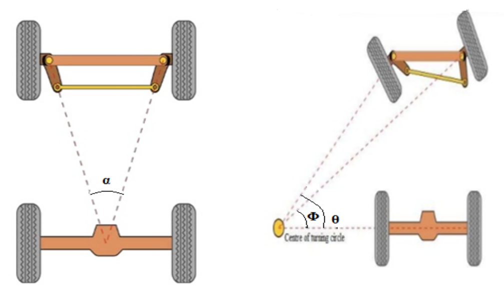


Fig. 1. Ackermann Principle and Inner wheel and Outer wheel angles

The intention of Ackermann geometry is to prevent the tyres from slipping outwards when the wheels follows around a curve while taking a turn. The solution for this is that all wheels to have their axles settled as radii of circles with a common centre point. Since the rear wheels are fixed, this centre point must lie on a line extended from the rear axle. So we need to intersect the front axle to this line at the common centre point. While steering, the inner wheel angle is greater than outer wheel angle. So for obtaining different results we need to vary the parameters in order to obtain desired steering geometry.

II. CALCULATIONS

In the figure below it is shown that the total length of the vehicle from the center of the front wheel to center of the rear wheel is called Wheel Base (b). Similarly, the total length between center of the front left wheel to center of front right wheel is called Wheel Track (t). The distance between the two pivot joints of steering system is called Kingpin Centre to Centre distance (k). The calculation of Ackermann angle is shown below:

TABLE I. PREDEFINED VALUES OF THE VEHICLE

Quantity	Value
Wheel base (b)	50”
Wheel track (t)	46”
Kingpin C-C distance (k)	38”

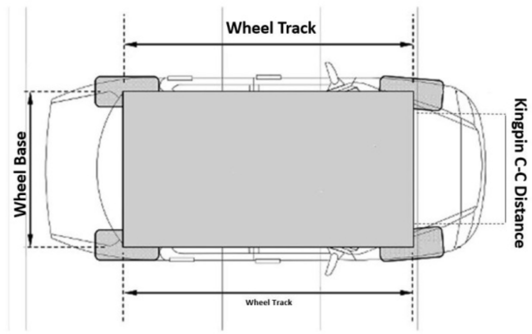


Fig. 2. Wheel Track, Wheel Base and Kingpin C-C Distance

Ackermann angle (**α**) = $\tan^{-1}$ [(kingpin distance/2) / wheelbase]

$= \tan^{-1}$ [(38/2) / 50]

$= \tan^{-1}$ [0.38]

= 20.80

But, according to Ackermann geometry for correct steering, the below equation should be satisfied, thus by calculating Inner Wheel angle and Outer Wheel angle practically were:

$\Phi = 27^\circ$

$\theta = 43^\circ$

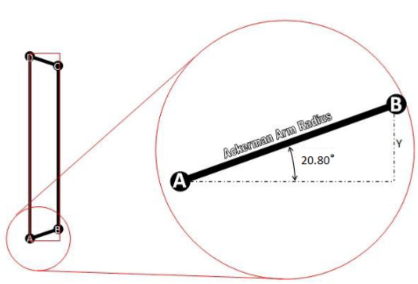


Fig. 3. Ackermann Arm Radius

A. ARM BASE CALCULATIONS:

Arm base is a part of steering knuckle, to which the tie rods are attached. We know that sine angle in a triangle is the ratio of opposite side to hypotenuse, thus,

$\sin \alpha = Y/R$

Where, Y= arm base

R= arm radius assumed to be 5”

Sin 20.80 = Y/R

Y=1.7”

Thus the value of Ackermann arm base is 1.7”

B. TURNING CIRCLE RADIUS:

Turning circle radius is the full diameter of the smallest circle traced by the wheels when taking a full turn,

$$T_{OF} = \frac{b}{\sin \Phi} + \frac{(t-k)}{2}$$

$$T_{IF} = \frac{b}{\sin \theta} - \frac{(t-k)}{2}$$

Outer wheel turning circle radius:

T_{IF} = 1.96 m

Inner wheel turning circle radius:

T_{OF} = 2.695 m

Average turning circle radius (T_{AVG}) = 2.35 m

C. RACK AND PINION CALCULATIONS:

TABLE II. Values of the quantities used in calculations

Quantity	Value
Rack length	5”
Rack shaft length	15”
Number of teeth on rack	27
Number of teeth on pinion	18
Diameter of pinion	27 mm
Module of rack and pinion	1.5mm
Pressure angle	20°
Addendum	1.5 mm
Dedendum	1.875 mm

We know that, $\text{module} = \frac{\text{Diameter}}{\text{Number Of Teeth}}$

Module of rack and pinion = 1.5 mm

Steering wheel lock to lock angle is the total rotating capacity of the steering wheel (i.e. -270° to +270°). Steering Ratio is the ratio of Input from the steering wheel (in degrees) to the output on the wheels (in degrees).

Steering wheel lock to lock turns / angle = 1.5 turns/ 540°

Steering ratio = 270 / 43 = 6.2: 1 = 6:1 (approx)

D. STEERING WHEEL TORQUE CALCULATION:

The torque required to rotate the steering wheel by the driver is called Steering Wheel Torque (W_T).

The calculations for steering wheel toque as follows,

$$T = Wu\sqrt{\frac{B^2}{8} + E^2}$$

T = kingpin torque
W = axle weight = 50 kg = 120 lbs (the axle weight for every vehicle is different and it is not the total weight of the vehicle)
u = co-efficient of friction = 0.7 (assumed to be 0.7 for most of the road condition)
E = kingpin offset = 55mm = 2.1”
B = width of tire = 7”

The above values will be different for every vehicle.

$$T = 50 * 0.7\sqrt{\frac{7^2}{8} + 2.1^2}$$

=113.60 inch-lbs
=12.84 N-m

Torque on Pinion gear = $\frac{\text{Torque}*\text{Gear Ratio}}{\text{Diameter Of Pinion}}$

$$= \frac{12.84*0.66}{0.0165}$$

= 513.6 N

Steering wheel torque = 513.6 * 6 * 0.0254
= 78.27 N-m

The values of Steering Effort, Gear ratio, Steering Ratio for different predefined Pinion sized are shown below, the table shows that the change in pinion size is directly proportional to the steering effort applied by the driver and the steering ratio. And similarly pinion size is inversely proportional to Total steering lock to lock angle. The turning circle radius is independent of pinion size and remains constant in the table. Therefore, for vehicles with heavy axle loads should prefer smaller pinion pitch circle diameter.

TABLE III. Different quantity values for various Pinion Sizes

Pinion Size	Steering Ratio	Steering Effort	Steering L-L Angle	Gear Ratio
15mm	11.2 : 1	31.2 N	970° (2.69 turns)	0.37
21mm	8 :1	43.68 N	693° (1.925 turns)	0.51
27mm	6.2 : 1	56.01 N	540° (1.5 turns)	0.66
33mm	5 : 1	68.64 N	440° (1.22 turns)	0.81
39mm	4.3 : 1	81.05 N	373° (1.03 turns)	0.962

Similarly, for predefined Rack lengths, the values of Inner wheel angle, Outer wheel angle, Lock to Lock Steering wheel angles and Average Turning circle radius are shown below, the table shows that Rack length is directly proportional to the steering wheel lock to lock angle and inversely proportional to average turning circle radius.

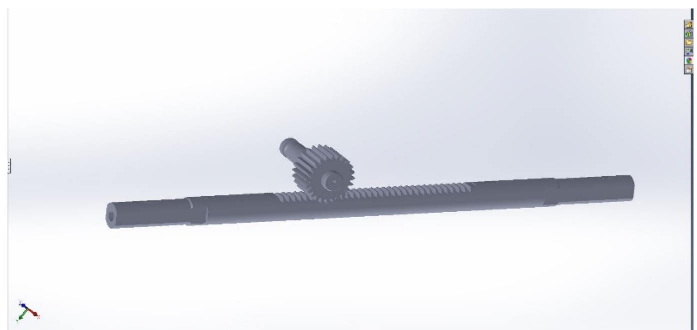
TABLE IV. Different quantity values for various rack lengths

Rack Length	L-L Angle	θ	Φ	T_{AVG}
3.5”	378°(1.05 turns)	30.1°	18.9°	3.22 m
4”	432°(1.20 turns)	34.4°	21.6°	2.85 m
4.5”	486°(1.35 turns)	38.7°	24.3°	2.56 m
5”	540°(1.50 turns)	43°	27°	2.33 m
5.5”	594°(1.65 turns)	47.3°	29.7°	2.14 m
6”	648°(1.80 turns)	51.6°	32.4°	2.01 m

Where,
Φ = outer wheel angle
θ = inner wheel angle
T_{AVG} = Average turning circle radius

III. CAD MODEL

We have designed complete assembly of rack and pinion in SOLIDWORKS 2015, the complete design of rack and pinion and its assembly in SOLIDWORKS 2015 is shown below:



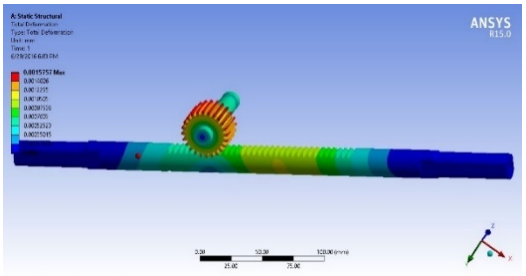
IV. ANALYSIS OF COMPONENTS

Analysis is process of analysing the components by applying load, temperature, pressure etc. and obtaining the values such as stresses (bending, tangential and normal), deformations, safety factor etc. in order to determine the safety of the components when done in practical. These Analyses gives optimum result of safety of components and minimize the chances of failure.

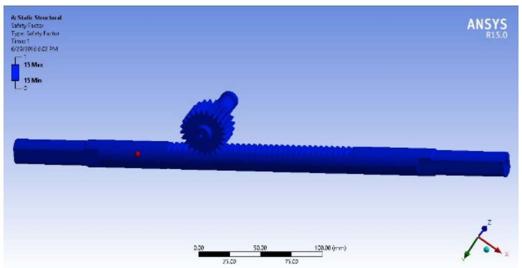
Three major analyses of rack and pinion on Ansys 15.0 are carried out here:

1) Total Deformation
2) Equivalent Stress
3) Factor of Safety

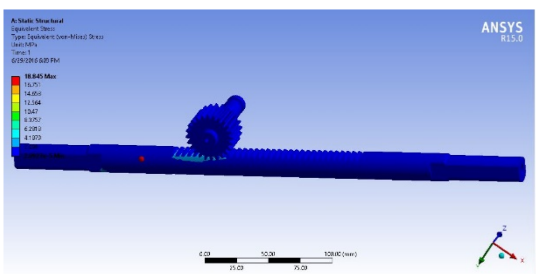
a) Total Deformation



b) Factor of Safety



c) Equivalent Stress



Material Type: EN24
Ultimate Tensile Strength = 850 MPa
Maximum Stress Obtained = 18.845 MPa
Factor of Safety = 15
Maximum Deformation = 15.5757 x 10^{-4}mm
Thus after the analyses of components The Design is Completely Safe.

V. CONCLUSION

The manual rack and pinion steering system is not used in heavy weight vehicles due to high axle loads, although it is simple in design and easy to manufacture, therefore it is commonly used in light weight vehicles. The values calculated in the paper may differ practically due to steering linkages error or due to improper steering geometry, so these values are useful to understand the interdependency of the quantities on each other and to design a ideal manual rack and pinion system for the vehicle.

REFERENCES

[1] R.S. Khurmi, J.K. Gupta "Theory of Machines", S. Chand & Company Pvt. Ltd., Vol 1, 14th Edition, 2014.

[2] S.K. Gupta "A Textbook of Automobile Engineering", S. Chand & Company Pvt. Ltd., Vol 1, 1st Edition, 2014.

[3] Saket Bhishikar, Vatsal Gudhka, Neel Dalal, Paarth Mehta, Sunil Bhil, A.C. Mehta "Design and Simulation of 4 Wheel Steering System", International Journal of Engineering and Innovative Technology (IJEIT), Volume 3, Issue 12, June 2014.