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FINAL DRIVE TRANSMISSION SYSTEM: OPTIMAL DESIGN

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Abstract - The goal of this project is to modify the drive transmission drive system of a 65 HP tractor. A spur planetary drive system is proposed, which has a number of advantages over the traditional cylindrical spur gear drive system. It has a high torque capacity, is smaller, more efficient, and weighs less. Because gears are one of the most important design elements, failure of one gear can have a significant impact on the entire drive system, which can be caused by stress, contact pressures, or temperature. Gears for spur planetary drives are constructed with safety criteria such as tooth root strength, pitting resistance, and scuff resistance in mind. When compared to cylindrical spur gear drives, these gears are much safer. The paper also focuses on modeling of cylindrical gears with spur planetary drive system using KISSsoft and assembly of spur planetary drive and rear axle housing of 65HP tractor using Solid Works.

Keywords— Transmission system, Planetary, Tractor, Solidworks, Scuffing, Pitting

1. INTRODUCTION

The transmission mechanism in an off-road vehicle transfers engine power to the rear wheels via gears. It slows the vehicle's speed while increasing torque at the same time using various gear drives. The gearbox, intermediate housing, and main transmission housing make up the transmission mechanism, with the final drive going to the back wheel via portals. In the portals, there is a significant fall in speed. Between differentials and drive wheels, final drive is a gear reduction mechanism in the power train. The power is finally transferred to the rear axle and wheels by final drive. The back wheels of the tractor are not directly connected to the half shafts; instead, the drive is transmitted through gears.

2. PROBLEM STATEMENT AND ASSUMPTION

The goal of this project is to construct a final drive system using a spur planetary gear arrangement in order to address the disadvantages of the existing final drive cylindrical spur gear pair mechanism, which uses a ring and pinion configuration.
Various methodologies were used to optimize housing weight, transmission system efficiency, and gear pair design, and it was concluded from all of the data that planetary design saves weight over cylindrical spur gear pair [1].

3. EXISTING MECHANISM

The spur gear is a cylindrical shaped gear in which teeth are parallel to the axis. Each half shaft terminates in a small gear which meshes with a large gear called gear wheel. The gear wheel is mounted on a shaft, carrying the tractor rear wheel. The device for final speed reduction, suitable for tractor rear wheels is known as final drive mechanism. Reduction gear ratio of the final drive is determined by number of teeth on the ring gear divided by number of teeth on the pinion gear. Below in table 3A basic geometric specifications of gears of cylinder spur gear pair final drive mechanism is shown.

TABLE 3 A: GEOMETRY CHARACTERSTICS

	Cylindrical Spur Gear Pair	
	Pinion Gear	**Ring Gear**
Material	20 MnCr 5, Case-carburized steel, case-hardened	
Module	5.5	5.5
Number of teeth	14	59
Pitch Circle Diameter	77	324.5

Module is the basic parameter in gear geometry and describes the size of gear. As the module increases, the size of gear teeth increases. In the existing mechanism 5.5 module is taken.
Gear ratio = (teeth on ring gear)/(teeth on pinion gear) = 59/14 = 4.214

Material use for the gears in cylindrical spur gear pair is 20 MnCr 5, case-carburized steel. Surface hardness of gear wheel and pinion gear is HRC 60. Gears of gearboxes in most tractors are produced from 20MnCr 5. With the help of KISSsoft calculations of cylindrical spur gear pair are entered. The existing design of 65 HP tractor meshing gear wheel and pinion gear is shown in figure.

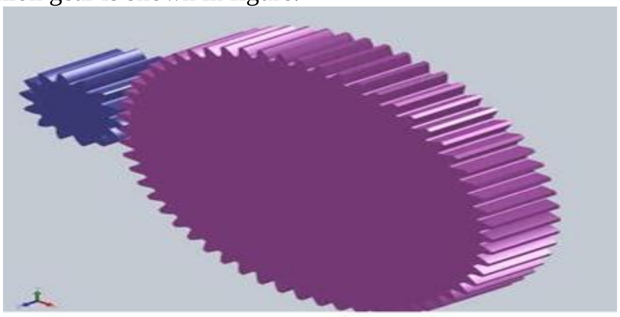


Figure 3 a – Meshing gear wheel and pinion gear

TABLE 3 B: COMPUTED VALUES

	Cylindrical Spur Gear Pair	
	Pinion Gear	Ring Gear
Power (KW)	27.818	
Speed (1/Min)	54.0	12.8
Torque (Nm)	4919.3	20731.1
Required service life [H]	5000.00	
Gear driving (+) / driven (-)	+	-

All the geometric values of gears influence the whole final drive transmission system. Meshing efficiency of gears is 97.602 for cylindrical spur gear pair final drive. These entered values compared to the calculations of new design.

TABLE 3 C: GEOMETRY DETAILS

	Cylindrical Spur Gear	
	Pinion Gear	Ring Gear
Total Power Loss (KW)	0.667	
Weight –calculated (Kg)	3.790	42.922
Total Weight	46.713	

4. DISADVANTAGE OF EXISTING FINAL DRIVE

Housing and casting of gear wheel (bull gear) and pinion is big that‘s why space requirement is more in cylindrical spur gear pair mechanism of final drive transmission. Weight of gear wheel is more in cylindrical spur gear pair due to larger size of gear wheel. Velocity reduction is lower in cylindrical spur gear pair final drive mechanism. Lubrication oil used to lubricate the gear wheel and pinion is more in cylindrical gear pair due to more space requirement of housing and casting of gear wheel and pinion. Contact ratio is less in ring and pinion type final drive mechanism. Initial cost of final drive system is more.

Permissible tooth root stress is more in case of cylindrical spur gear pair and safety for tooth root stress is not as per the required safety. Therefore the gear is not safe. In the condition of tooth root strength transmittable power of cylindrical spur gear pair is lower. Pitting is the major cause of gear failure, occurs during transmission of torque or due to compressive fatigue on the gear tooth surface. When safety considered against pitting (tooth flank) safety for surface pressure at operating pitch circle is lower than the required safety. Therefore transmittable power is lower in cylindrical spur gear pair. In cylindrical spur gear pair brakes takes extra space for brake housing therefore larger space occupied and having more weight when compared to the spur planetary final drive as in this mechanism brakes are attached in the same housing of final reduction.

5. PROPOSED MECHANISM

Planetary gear sets are used in many applications, ranging from gas turbines to automotive power trains. They provide a large set of different transmission ratios. Improved efficiency relative to fixed axes transmission systems is one of the most important advantages of planetary gear sets [2]. Spur are often used because they are the simplest to design and manufacture, and are the most efficient, as well. Spur gears have straight teeth that are situated parallel to the gear axis. They are most commonly used in power tools and robotics applications. As the spur gear gives maximum operating efficiency therefore in the new design of final drive spur gears are used for planetary final drive. Planetary gear has advantages of compact structure, large transmission torque, stable transmission and high efficiency. It is widely used in various mechanical settings. Li et al., 2013 [3]

The terminology ‘planetary transmission’ comes from the gear arrangement similar to that of planets in solar system. A sun gear is located at the centre of mechanism and is in mesh with several planets which orbit around it. The planets are mounted on carrier which can either be fixed or rotating. Fig shows a schematic representation of planetary gear set comprising planet gears, a sun gear, a ring (internal) gear and a planet carrier (a relatively rigid structure that supports the planets).
Fig 5.1 shows planetary gear wheel hub system, including the power flow from the differential gearbox through to the wheel hubs. Power is transmitted through the sun gear, attached to the input shaft. The ring gear is fixed to the housing. The output power is transmitted to the wheels through the carrier. The planetary system comprises three planet gears. It is assumed that there is no misalignment in the planetary system, and the input power from the sun gear is equally divided among the planets [4].

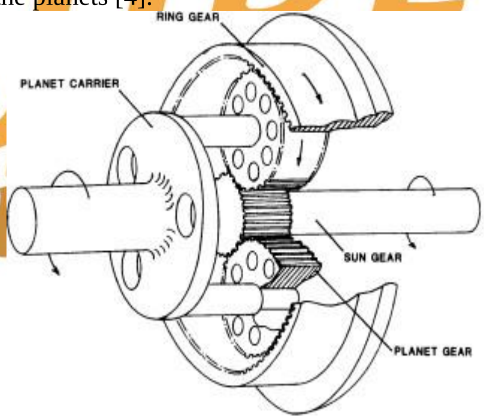


Fig. 5 a – Planetary Gear [5]

The schematic model of planetary gear arrangement considered in the present study is shown in figure Planets are free to rotate and also translate with respect to the carrier. Planetary axles can be placed at regular pitch as there are three planet gears and all are at equal angles. Spur planetary gear is used to perform speed reduction due to several disadvantages of cylindrical spur gear pair system. Spur planetary gear mechanism is used to obtain high power density, large reduction in small volume and pure torsion reactions. Another advantage of the spur planetary gear final reduction arrangement is load distribution as the load being transmitted is shared between multiple planets and therefore the torque capability is greatly increased. The more the planets in the mechanism, the load ability of mechanism increase and which increase the torque density. Here three planet gears are used and the load is distributed between the three planet gears. To transmit the torque, one of the gears must be held stationary from sun gear, the carrier or the annular gear. Here ring gear also known as annular gear is held stationary and the sun gear shaft is driven by keeping the annular gear fixed. Planetary gear rotates around their axes simultaneously.

Spur planetary gear is used to perform speed reduction due to several disadvantages of cylindrical spur gear pair system explained above. As three planet gears are used therefore the load is distributed is between the three planet gears and to transmit the torque, one of the gears must be held stationary from sun gear, the carrier or the annular gear. Ring gear also known as annular gear is held stationary and the sun gear shaft is driven by keeping the annular gear fixed. Planetary gears rotate around their axes simultaneously. Gears are one of the most critical components to design which determines the capability and reliability of derive system. Therefore in mechanical power transmission system and in industrial rotating machinery gears is the most critical component. The layout, speed, power transmission and interconnections of gear pairs of transmission systems for the 65 HP tractor model are considered to be same only final reduction is affected in spur planetary final drive due to equal distribution of load on the planets. Existing final drive mechanism of ring and pinion arrangement has reduction ratio at portal is taken as a constraint by which planetary final drive is designed.
Existing final reduction ratio = teeth on driven gear teeth on driving gear = 59/14 = 4.214

4.214 is gear ratio which is the constraint to design the gears of spur planetary system. According to gear ratio sun gear, planet gears, ring gear are generated in KISSsoft where factors are considered like tooth geometry and material, factors of general influence and factors of failurewhile designing the gears.

Gear ratio in planetary arrangement = (teeth on driven gear)/(teeth on driving gear)

= (teeth on planet carrier) /(teeth on sun gear)

= $(T_s + T_a) / T_s$

= 4.214 (taken equal to existing gear ratio)

$$\frac{Ta}{Ts} = 3.214$$

As T_a is number of teeth on ring gear and Ts is number of teeth on sun gear. Therefore to design spur planetary drivegear ratio of number of teeth on annular gear to the number of teeth on sun gear should be approximately equal to 3.214.

Ratio of number of teeth on annular gear and sun gear is approximately equal to

$$\frac{56}{17} \; or \; \frac{55}{17}$$

From the two values one value is selected which is nearer to 3.214 to design the final drive mechanism. Therefore from two values one value is selected which is 56/17.

One of the necessary parameter is module of gear which depends on loading and bending stress on the gear. Selected module for planetary arrangement is 4. Table 2.1 shows gear specifications of planet gear, sun gear and ringgear.

TABLE 5 A: SPECIFICATIONS OF GEAR SYSTEM

Gear Specification			
	Planet gear	Sun gear	Ring gear
Material	20 MnCr 5, Case- carburizedsteel, case- hardened		
Module	4	4	4
Number of teeth	18	19	59
Pitch Circle Diameter	72	76	236

Material quality is according to ISO 6336:2006 normal. KISSsoft is world class software for the gear design and power transmission, which is being used by many companies like Daimler Benz, Toyota. KISSsoft or KISSsys allow us to model any type of gear transmission and analyses various components like gears, shafts etc. KISSsoft is best known for its in-depth gear analysis capabilities. KISSsoft/ KISSsys are to calculate the strength or lifetime of elements that are based on the standards such as ISO, DIN, and AGMA. The software is to improve the efficiency and safety of the design. While designing a final drive system, an iterative process must carry out. For every change of an element of final drive system for example module of gear influences other parts like the bearing loads. Checking theses influences by manual calculation is extremely slow and prone to errors. Therefore the objective is to parameterize the pair of gear like standard software does. This is achieved with KISSsoft. A three dimensional graphical presentation of the current state of the system immediately shows the geometrical influence of every change in parameters. This approach greatly accelerates the design process and results in a balanced design even during the concept phase

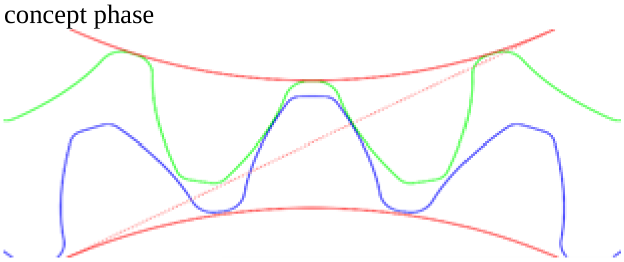


Fig. 5 b – Meshing of Gears

The changes in gear tooth geometry results changes in meshing contact conditions and therefore gear contact and stresses change.

Gears are one of the most critical components in power transmission system in which failure of one gear will affect the whole transmission system. It can lead to various failures which cause noise, vibration etc in the system and cost of replacement of spur gear is very high. Failure of gear cause breakdown of whole system. There are various factors which can lead gear failure therefore to make the gear safe safety factors are considered. Failure of gear characterized by either of three modes of failure:- Tooth Root Strength - fatigue is the most common failure in gearing. Two most common modes of fatigue failure in gear is tooth bending fatigue and surface contact fatigue. Pitting – Pitting is the phenomenon in which small particles are removed from the surface of tooth because of the high contact forces that are present between mating teeth. The primary property of the gear which provides resistance to pitting is the hardness of gears. Micro- pitting or pitting (Contact fatigue failures modes) can eliminated through proper selection of material, lubrication method and surface engineering technique. Pitting under pure rolling can occur even under proper lubrication conditions, since oil, as an incompressible fluid, will merely transmit the contact loads [6].

In a final drive transmission system design, it is quite difficult for a designer to quickly find an optimum solution, while the space restriction is given and weight is to be minimized. Also the total power cost and other relevant factors have to be optimized. Solving such a problem is very time consuming if different variants of reducer have to be evaluated carefully. Therefore a new optimization tool is used; KISSsoft is a software package for calculating machine elements. While gears are a natural focal point, owed to their central role in transmission, the software also covers shafts, bearings, connecting elements, springs, belts and others. Gears calculations cover all common gear types: cylindrical gears, bevel gears, worm gears, helical gears, hypoid gears and face gears, for cylindrical gears also as planetary sets and gear racks [7]. Tooth geometry calculations are according to DIN 3960:1987. Geometric calculations of gear calculated from KISSsoft. Table below are the geometries of gear for sun gear, planet gear, ring gear.

TABLE 5 B: TOOTH GEOMETRY OF GEARS

	Gear 1	Gear 2	Gear 3
Centre Distance(mm)	79.00		
Pressure Angle at Normal Section (°)	20.00		
Contact Ratio		1.039	1.162

Type of lubrication oil used in spur planetary final drive is ISO VG 220 and the gears are fully immersed in oil. Specific density of oil at 15° C is 0.895 kg/dm³ and the temperature of oil is maintained at 70° C. the geometry given above influence the other factors which are below in the table. The changed geometry factors of sun gear, planet gear and ring gear and their change tooth geometries influence efficiency and total weight of spur planetary gear final drive arrangement.

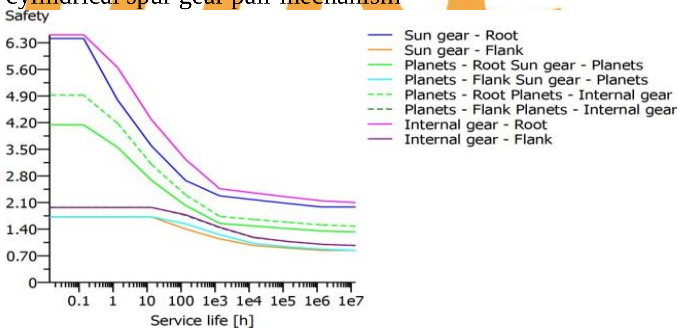
TABLE 5 C: MODIFIED GEOMETRIC INFLUENCES

	Spur Planetary Gear		
	Gear 1	Gear 2	Gear 3
Total Power Loss (KW)	0.220		
Total efficiency	0.976		
Weight –calculated(Kg)	2.214	2.013	5.429
Total Weight	13.682		

6. COMPARISON

Optimization of final reduction mechanism from cylindrical spur gear pair mechanism to spur planetary gear mechanism is done using KISSsys software that permits to layout automatically a complete final reduction mechanism and their parameters. It is necessary to choose a quicker way of evolution for the performance of gear teeth, regardless of the material of construction and manufacturing process adopted.
The performance parameter like tooth bending, surface distress and tooth deflection are the basic modes of fatigue failure of any toothed gearing Carl C Osgood, 1970 [8]. The case hardened material is used in the final reduction mechanism arrangement. Case hardened materials commonly used in highly loaded gears. The gear wheel is a machine element that has puzzled many engineers, as numerous technological problems arise in a complete mesh cycle. The designer has to make the most durable design that will allow for good economy and performance for the end user the result of course depends on the segment to which the end user belongs.

Factor of safety is used to provide a design margin over the theoretical design capacity to allow for uncertainty in the design process. Factor of safety to be used in this design is essentially a compromise the benefit of increased safety and reliability. The table describes the safety factor for tooth root stress on the gears of final reduction mechanism and comparing spur planetary gear final reduction mechanism and cylindrical spur gear pair mechanism



Safety factor curves
Due to high service load, harsh operating conditions or fatigue, faults may develop in gears [9]. Gear faults are re-sponsible for approximately 60% of gearbox failures. Most of these come from damage on the gear teeth such as pitting, cracking, and spalling [10]. Through observations at Syncrude Canada Ltd, fatigue crack and tooth pitting were the two commonest failure modes [11].
TOOTH ROOT STRENGTH:

TABLE 6 A: SAFETY CALCULATIONS IN TOOTH STRENGTH

	Spur Planetary Gear			Cylindrical Spur Gear Pair	
	Gear1	Gear 2	Gear 3	Gear1	Gear 2
Required Safety	1.40	1.40/1.40	1.40	1.40	1.40
Safetyfor ToothRoot Stress	2.22	1.51/1.69	2.40	0.63	0.52

TABLE 6 B: POWER TRANSMISSION COMPUTATION

	Spur Planetary Gear			Cylindrical Spur Gear Pair	
	Gear1	Gear 2	Gear 3	Gear 1	Gear 2
Transmittable Power (KW)	14.69	10.02/11.20	15.90	12.57	10.36

SAFETY AGAINST PITTING

Pitting takes place due to large contact pressure occurring between the tooth surfaces. Fatigue cracks set up due to the repeated contact stress and the cracks get developed into pits resulting in ultimate failure of the teeth. Maximum pitting occurs on the tooth face because tooth loading is cyclic. Pitting is a surface fatigue failure that occurs when the endurance limit of the material is excluded this failure nature depends on surface contact stress and number of stress cycles. Initial pitting is usually caused by gear tooth surface not fitting together properly and not properly conforming to each other. The criterion for surface durability is based on the Hertz pressure on the operating pitch point.

TABLE 6 C: SAFETY FACTOR FOR PITTING

	Spur Planetary Gear		Cylindrical Spur Gear Pair	
	Gear 1 Gear 3	Gear 2	Gear 1	Gear 2
RequiredSafety	1.00 1.00	1.00/1.00	1.00	1.00
Safety forSurface Pressure at OperatingPitch Circle	1.02 1.29	1.12/1.28	0.54	0.62

TABLE 6 D: POWER TRANSMISSION COMPARATIVE DETAILS

	Spur Planetary Gear			Cylindrical Spur Gear Pair	
	Gear 1	Gear 2	Gear 3	Gear1	Gear2
Transmitable Power (KW)	8.79	10.53/15.30	15.54	12.57	10.36

	Spur Planetary Gear		
	Gear 1	Gear 2	Gear 3
Total PowerLoss (KW)	0.220		
Total efficiency	0.976		
Weight – calculated withTip Diameter (Kg)	2.214	2.013	5.429
Total Weight	13.682		

7. DESIGN AND MODELING

In the study, Gears of spur planetary final drive are modeled in KISSsoft by using gear ratio of existing final drive mechanism. Gears are generated by taking some criteria for spur planetary final drive system. Generated gears for final drive are one ring gear, one sun gear, and three planet gears.

GENERATION OF GEARS

The gears are generated in KISSsoft which is shown in figure 6.1

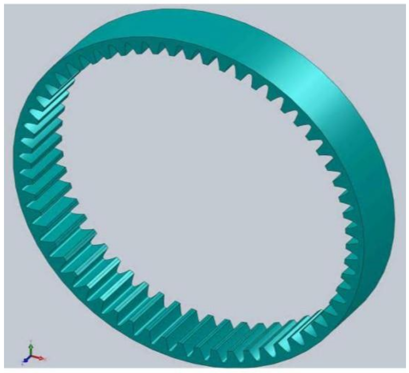


Fig. 7 a – Ring Gear

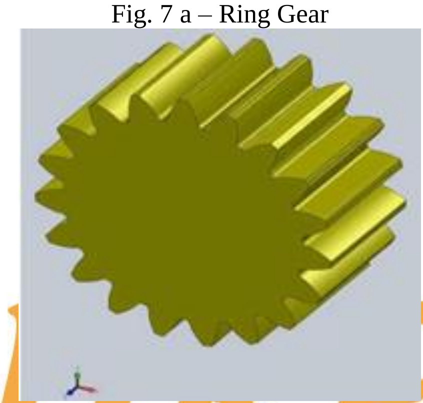


Fig. 7 b – Sun Gear

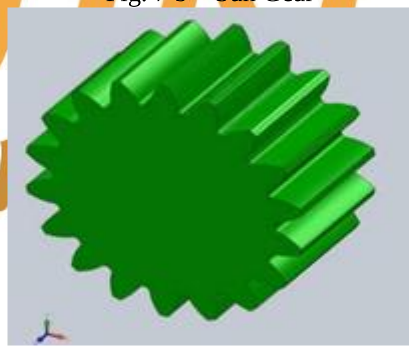


Fig. 7 c – Planet Gear

Figure 7.4 Generated gears using KISSsoft shows a full mechanical design assembled planet gear system with following main components sun gear, ring gear, planet gear

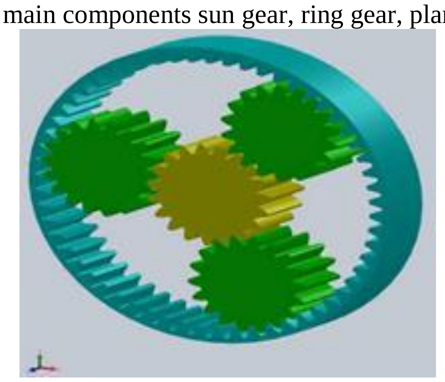


Fig. 7 d - Assembled spur planetary gear arrangement

After the assembly of gears for spur planetary final drive system full assembly is done by attaching carrier, bearing and other components. The spur planetary final drive system is mounted on the rear axle housing with the bolts. The rear axle housing is attached to the wheel shaft. The rear axle housing has to be in a horizontal position so that bolts of ring gear of final drive system could be mounted on the rear axle housing. The transmission left-hand (LH) and right-hand (RH) outputs are connected via toothed, sliding couplings to the sun gears of the LH and RH final drives, respectively. As the ring gears of the two final drives are fixed, and they provide the reaction torque. The output power from the LH and RH final drives is taken from the planet carriers, which are connected to the LH and RH sprockets driving the tracks.

The rear axle housing in fig. 4.5 is the optimized housing and the parameters are altered according to the original rear axle housing in Solidworks.

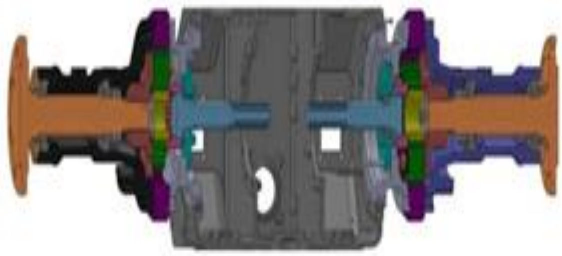


Fig. 7 e – Sectional view of rear axle housing

MOTION CONVENTION PLANETARY DRIVE:
For the combined rotation and revolution of planet gear two steps taken into account. The first step is to lock the whole assembly and rotate the whole assembly even the ring which is fixed, in one turn CCW. (Chaudhari et al 2014.)

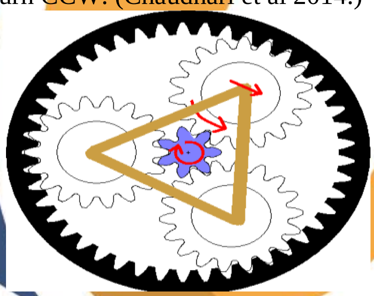


Figure 7 f: Motion of planetary drive (Ludin and Mardestan, 2010) [12]

The motions are entered into the table using the convention: CCW = Positive CW = Negative

	Sun	Planet	Ring	Carrier
Rotate whole assembly CCW	-1	+1	+1	fixed

8. CONCLUSIONS

Primary objective of this research work is to reduce weight of final drive transmission and to generate safer gears for final drive. This objective is achieved with the help of experimental investigations. Weight of spur planetary final drive is lower than existing system by33.031 kg. Space due to the tooth geometry and gear geometry for new arrangement of final drive is lesser than existing making spur planetary final drive compact in size. Gears of spur planetary final drive are safer in case of tooth root strength, pitting and scuffing than cylindrical spur gear pair final drive and therefore life of gears is more as compare to existing system. Hence present analysis shows that spur planetary final drive is more efficient than cylindrical spur gear pair final drive mechanism in 65 HP HMT make tractors. The comparisons show that the gears in spur planetary gear final reduction mechanism are much safe than the gears of cylindrical spur gear pair mechanism as the value of safety for tooth root stress and pitting is less than required safety. Therefore spur planetary gear final reduction mechanism is more efficient than spur cylindrical spur gear pair mechanism.

Table above shows the transmittable power in spur planetary gear and cylindrical spur gear. The differences conclude that spur planetary gear final reduction mechanism is the more efficient than cylindrical spur gear pair as the maximum power transmit in spur gear final reduction mechanism is more than cylindrical spur gear pair at tooth root strength and pitting.

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