International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 05, May - 2017

Modal and Stress Analysis of Gear Train in Portal Axle System

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***Abstract* - Portal axle is a gearbox designed to increase the ground clearance of the vehicle for off-road driving conditions. The higher ground clearance depends on the arrangement of gear train of the portal axle. The gear train and shafts are the most critical part in the portal axle as they transmit and withstand very high loads. They should be designed to withstand overloading and lightweight for greater durability and performance of the portal axle. Stress and vibration analysis of the gear train and shafts are necessary in evaluating the design for gear train and shaft. The setup of experiment for investigating the vibration behavior of the gear train in the portal axle can be expensive and difficult due to the complexity of gear parts to be tested upon. The axle tube is above center of wheel hub and where there is a reduction gearbox in the hub. It is installed between the wheel and the axle shaft to give higher ground clearance to the vehicle. In this work portal axle system is designed with spur gear train and helical gear train. Both system are analyzed by Finite Element Analysis and experimentally to find out better gear train system for portal axle.**

Keyword : Portal Axle, Spur gear train, Helical gear train, FEA, Experimental analysis

1 INTRODUCTION

Portal axles (or portal gear) are an off-road technology where the axle tube is above the center of the wheel hub and where there is a reduction gearbox in the hub. This gives two advantages: ground clearance is increased, particularly beneath the low-slung differential housing of the main axles[1]; and secondly hub gearing allows axle half shafts to drive same power but reduced torque. This reduces load on axle crown wheel and differential.

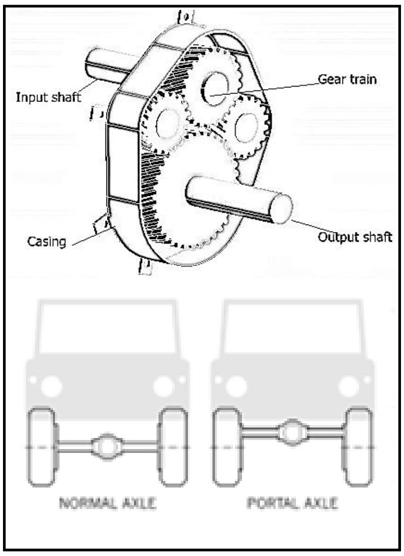

Fig. No. I Portal axle system

Compared to normal layout, portal axles enable the vehicle to gain a higher ground clearance, as both axle tube and differential casing are tucked up higher under vehicle. Size of the differential casing can be reduced to gain even more ground clearance. Additionally, all drive-train elements, in particular transfer gearbox drive-shafts, can be built lighter[2]. This can be of use in lowering center of gravity for given ground clearance. To be able to drive off the pavement, off-road vehicles need several characteristics. [3] The portal axle designed to give desired ground clearance to the vehicle system. In the project the design of this portal axle is to be carried out for different gear train as spur & helical and hence to do comparative study for both the gear trains[4]. The input shaft, gear train and output shaft is mainly design for portal shaft. The analysis will perform by FEM approach using CAD (creo) model & ansys software. The experimental analysis is also performing to get better results[5].

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Fig. No.II Application of Off-Road Portal Axle System Vehicle[15]

2. LITERATURE REVIEW

"Manjunatha B, Malthesha P. J., Somashekar Hiremath", June 2014, "Design and Analysis of Input Shaft of a Portal Axle." The main objective of this project is design and analysis of input shaft of a portal axle unit with different thickness of hollow shafts. The portal axle input shaft models were modeled and analyzed using ANSYS software and validated through comparison of results with the analytical results. "E. Jayaram, M. Rambabu", April 2013, "Structural Analysis of Gear Train Design in Portal Axle Using Finite Element." The paper states that the portal axle is a gearbox that is specially designed for off-road driving conditions. It is installed between the wheel and the axle shaft to give higher ground clearance to the vehicle. "JongBoon Ooi1, Xin Wang1, ChingSeong Tan2", October 2014, "Modal And Stress Analysis Of Gear Train Design In Portal Axle Using FEM And Simulation." It investigated modal analysis on three different gear trains of the portal axle unit was studied using FEM simulation under free-stress state and pre-stressed state. The gear tooth maximum bending stress and contact stress were calculated using FEM for three different gear trains with respect to varying angular position involving single and double tooth contact. "Umesh Shinde, Deepak C Patil", June 2015, "Finite Element Analysis Of A Portal Axle Gear Train Using Metallic And Composite Spur Gears." In this paper the cast steel which used in is the first type of steel that allowed alloys to be added to the iron. Prior to this method, manufacturers had not been able to get steel hot enough to melt. By heating blister steel in a clay crucible placed directly into a fire, Huntsman allowed the metal to reach up to 1600°C. Melting allowed other elements, such as nickel, to be mixed into the metal, thus strengthening the steel. Cast steel has a rough finish. It often has surface holes created by gas bubbling during heating process. Elastic metal, this type of steel is very tough, having 4 times tensile strength of cast iron.

2.1 Literature Gap

From above literature it is found that the gear train design is the main part for portal axle but it is available for spur gear train. For helical gear train for portal axle there is no such analysis done. Also very few data is available for experimentation of portal axle unit. There is no such research on total stress analysis of portal axle with casings and bearings.

2.2 Problem statement

Portal axle unit is a special gearbox unit designed to increase the vehicle's ground clearance. This gearbox can also be regarded as off-road technology where the axle tube is above the centre of the wheel hub. It allows driving on off-road so that the vehicle can go over high terrains and obstacles. Portal axle is normally designed for spur gear-train system. But in this project the spur gear-train & helical gear train both are analyzed. Hence both gear-trains are compared on its performance.

2.5 Scope

The investigation of work is based on numerical analysis & experimental validation of spur & helical gear train system of portal axle unit. For numerical analysis the FEA approach carried on ANSYS is used to study detailed stress & vibrational analysis. The experimental torque transmission ability is also to be investigated to get comparative results for both gear trains.

2.1 Objectives

The main objective of project work is to design the portal axle for spur & helical gear-trains on the basis of input data. Also the FEA approach is being used to get the numerical results for both the gear-trains. In which the stress & vibrational analysis is performed to compared spur & helical gear-trains system. The next objective of study is experimental analysis of portal axle for both the drive-trains. In this the portal axle performance is analysed by experimentation for torque transmission test. The overall comparison is carried away to get exact results.

3 DESIGN OF PORTAL AXLE

The design of portal axle is based on following systems from both gear-train units as:

- Input shaft
- Output shaft
- Spur gear train unit
- Helical gear train unit
- Bearing
- Casing

The Input shaft, output shaft, bearings & casing are common design systems for both gear trains as spur & helical. The total ground clearance has to increase by 6 inch for both the spur and helical gear train as per the given input

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3.1 Design Of Input Shaft

The input shaft is designed on given input specifications of Mahindra Scorpio as:

Given:

Speed = 4200 rpm Power = 55 kW

Diameter, D = 96mm Length of shaft = 500mm

Material selection:

The material selection of input shaft is based on toughness, hardness and availability of material. The material selected is EN24 steel. The material has high tensile strength.

Stress Analysis:

The following stresses are induced in the shafts:

1. Shear stresses due to the transmission of torque (i.e. due to torsional load).
2. Bending stresses (tensile or compressive) due to the forces acting upon machine elements like gears, pulleys etc. as well as due to the weight of the shaft itself.
3. Stresses due to combined torsional and bending loads.

As this Shaft is subjected to Combined Twisting Moment and Bending Moment, the shaft must be designed on the basis of the two moments simultaneously.

As EN24 is brittle material hence using Maximum normal stress theory or Rankine's theory the following equation is consider.

$\frac{1}{2}[M + \sqrt{M^2 + T^2}] = \frac{\pi}{32}\sigma_b d^3$ ....{Equation 1}

Where,

M = Bending moment of shaft (N/m) T = Torque (Nm)

σ_b = Maximum bending stress (N/m^2) d = Diameter of input shaft (m)

Ultimate Tensile/Compressive Strength = 850 N/mm^2

Taking FOS = 3

Hence, Diameter of Iutput Shaft is 40 mm.

3.2 Design Of Output Shaft

The output shaft of portal axle is designed on given input specifications of Mahindra Scorpio as:

Given:

Speed = 2800 rpm Power = 55 kW

Diameter, D = 96mm Length of shaft = 500mm

Material selection And Stress Analysis:

Same as Input Shaft

$\frac{1}{2}[M + \sqrt{M^2 + T^2}] = \frac{\pi}{32}\sigma_b d^3$ ....{Equation 2}

Where,

Ultimate Tensile/Compressive Strength = 850 N/mm^2

Taking, FoS = 3

Torque is given by:

1. Torque due to rotation:

$T_1 = P*60 / 2\pi N = 187.67$ Nm

2. Torque due to frictional force:

T_2 = Frictional force * radius of tyre = (0.5*200)*0.25 = 25 Nm

3. Torque due to Braking:

$T_3 = T_1 = 187.67$ Nm

So, Equivalent torque is:

$T = T_1 + T_2 + T_3 = 400.34$ Nm

Therefore, Dia. of Output Shaft is 40 mm.

3.3 Design of Spur Gear-Train

Material selection:

The material selection is based on toughness, hardness & availability of material. The material selected is EN24 steel. The material has high tensile strength.

Calculation of gear-train with intermediate gear

Given:

Power = 55 kW

N2 = 2800 rpm

Gear Ratio = 1.5

N1 = 4200 rpm

Tooth Bending Stresses produced is given by:

$$\sigma = \frac{W_t P_d C_v}{FY}$$

3.4 Design of Helical Gear-Train

Material selection:

The material selection is based on toughness, hardness & availability of material. Material selected is EN24 steel. Material has high tensile strength.

Calculation of gear-train with intermediate gear

Given:

power= 55 kw

N2= 2800 rpm

Gear ratio=1.5

Standard value of speed ratio for high speed helical gear is 1:1 to 10

Therefore,

N1 = 4200 rpm

Centre Distance: C = 150 mm = 0.15 m

3.5 Design for Bearing

Design of bearing is necessary for input & out shaft casing connection where the actual rotating motion & transfer of torque is carried out.

Actual Radial Load for Dynamically loaded bearing is:

$P = XVF_r + Y F_a$ or VF_r

Hence, Bearing selected is: Ball bearing 208

3.6 Design of Casing

The design of casing is as per the total measurement of gear train design. The casing is common for both the spur & helical drives

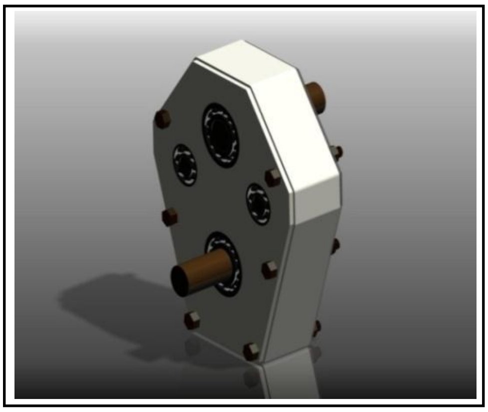

Fig. No. III CAD model of portal axle unit

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4 NUMERICAL ANALYSIS OF PORTAL AXLE

4.1 Stress Analysis Of Gear Train

In stress analysis modelling of the gear train, the gears required for the gear train are modelled based on the design parameters. The material properties and gear parts assembly are also assigned in this stage. This is followed by the FEA pre-processing stage where the mesh element, the load, and constraint are set on the gear train model. In order to determine the bending stress and contact stress accurately, different mesh element settings and FEA solver are required in separate setup. In the FEA post-processing stage, the FEA solution for the gear train model is completed. Thus, the bending and contact stress analysis can be performed by correlating the change in applied load and gear parameters. The following are the steps for stress analysis.

The input gear and output gear are positioned and constrained to mesh at a single tooth contact in between them. The gear contact surfaces between gears are aligned. In the FEA pre-processing, 'static structural' type is selected for the analysis by using ANSYS software. The mesh of the gear model is defined by using ANSYS mesh setting. When the gear tooth of the output gear is subjected to tangential load, the tooth root is the weakest point. Hence, tooth root area of output gear is meshed with higher density mesh.

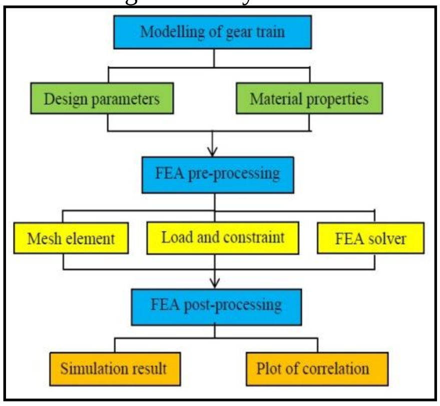

Fig. No. IV FEA general steps for obtaining the stress analysis

4.1.1 Stress analysis of spur gear train

4.1.1.1. Meshing

The stress analysis of spur gear train is carried out on ANSYS software. Fine meshing is done in a pre-processing of gear train model. The given generated mesh model of the gear train consisting of hexahedron elements, tetrahedrons elements and prism elements. From mesh model, number of elements & nodes 35397 & 112958 respectively.

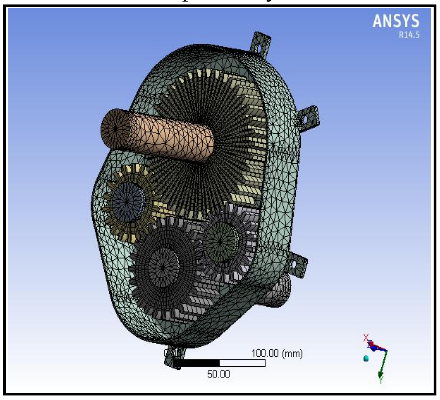

Fig. No. V Mesh model of spur gear train

4.1.1.2. Static structural equivalent stress

In the static structural approach the boundary conditions are set on the gear train in ANSYS setup. The load and surface constraints set in the ANSYS setup for simulating the static bending stress. Torque load of 25000Nmm and tangential cylindrical support are applied on the hub surface of the input gear. In the tangential cylindrical support, the surface is rigid and restricts the input gear to rotate about its axis. The driven gear's inner surface is fixed at hub surface to allow bending load at the gear teeth.

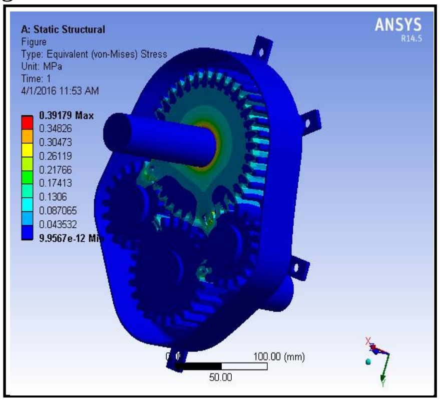

Fig. No. VI Static Structural model

4.1.1.3. Total deformation

The total deformation of spur gear train is obtained for given load.

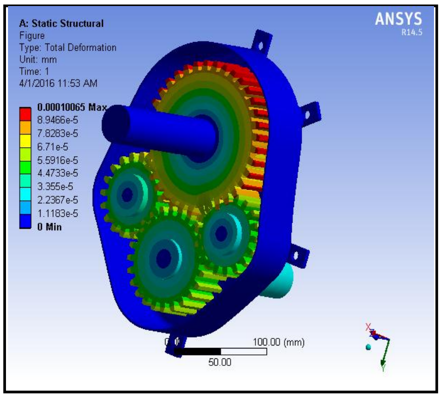

Fig. No. VII Total deformation

4.1.2 Stress analysis of helical gear train

4.1.2.1 Meshing

The stress analysis of helical gear train is carried out on ANSYS software. The fine meshing is done in a pre-processing of gear train model. The given generated mesh model of the gear train consisting of hexahedron elements, tetrahedrons elements and prism elements. From the mesh model, the number of elements , nodes are 181360 and 363413 respectively.

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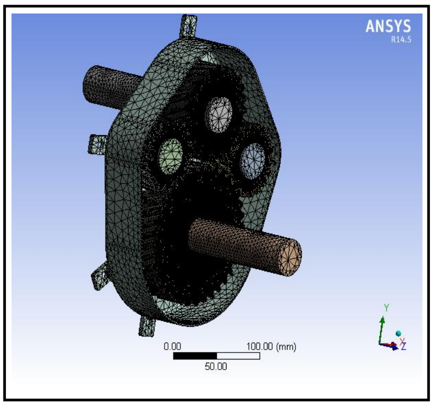

Fig. No. VIII Mesh model

4.1.2.2 Static structural equivalent stress

In the static structural approach the boundary conditions are set on the gear train in ANSYS setup. The load and surface constraints set in the ANSYS setup for simulating the static bending stress. Torque load of 25000 Nmm and tangential cylindrical support are applied on the hub surface of the input gear. In the tangential cylindrical support, the surface is rigid and restricts the input gear to rotate about its axis. The driven gear's inner surface is fixed at the hub surface to allow bending load at gear teeth.

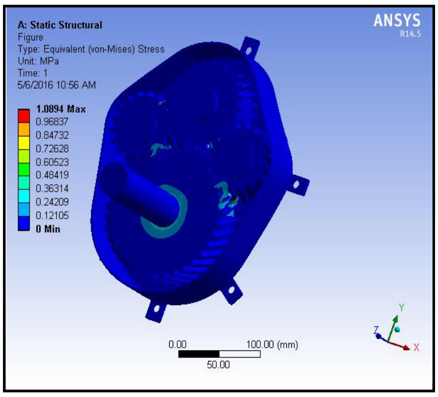

Fig. No. IX Static structural model

4.1.2.3. Total deformation

The total deformation of spur gear train is obtained for given load.

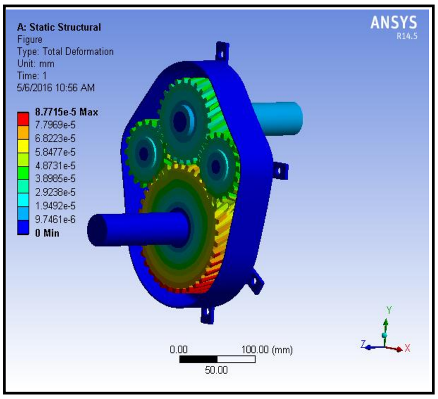

Fig. No. X Total deformation

5 EXPERIMENTAL ANALYSIS OF PORTAL AXLE

The experimentation has done to calculate the total torque transmission capacity of both the gear train drives. The experimental set-up is shown below. For the experiment setup the motor is used to give the input speed to the input shaft of portal axle drive. The input speed of shaft is varying by using dimmer sat instrument. Load to output shaft is varying by dynamometer. The 5 consecutive readings are taken to calculate the exact output torque of output gear of the portal axle.

5.1 Experiment Set-up

The actual experiment set-up is shown below:
The main parts of experiment are as:

- Motor
- Dimmer stat
- Dynamometer
- Structure

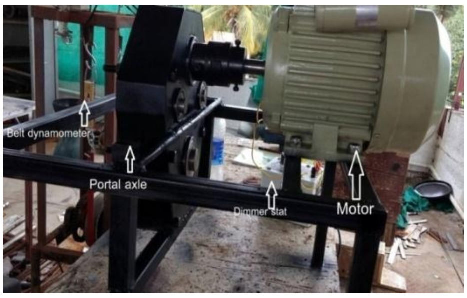

Fig. No. XI Experimental setup of portal axle unit for torque testing

5.2 Experimental Procedure

For the experiment the motor is used to give the input speed to the input shaft of portal axle drive. The input speed of shaft is varying by using dimmer stat instrument. The load to the output shaft is varying by dynamometer.

To analyse the torque output of portal axle the experiment is carried for two methods as:

1. Variable voltage method
2. Variable load method

5.2.1 Variable voltage torque analysis

In this method the given input voltage by motor to the portal axle input shaft is varying. For this method the dimmer stat instrument is used to vary the input voltage. Current is constant throughout the process. The consecutive 5 readings are taken to output shaft of portal axle. The RPM rating of output shaft is measured with help of digital tachometer.

5.2.1.1. Variable voltage torque analysis for spur gear train

In this analysis the voltage is varying while the current is taking constant.

The current is taking as 4 ampere throughout the process.

Table No. I Variable voltage torque analysis for spur gear train readings

Sr. no	Voltage (volt)	Output speed (RPM)
1	70	230
2	75	300
3	80	350
4	85	520
5	90	730

Calculations: Given:
Current = 4amp
Power factor = 0.85
Hence, Power (watts) = Current (amp)*Voltage (volt)*Power factor
Therefore, Power (watts) = 2πNT/60
Where, N = output speed (RPM)
T = Torque (N.m)
As per the calculations the torque is calculated as:

Table No. II Variable voltage torque analysis for spur gear train results

Sr. no.	Power (kw)	Torque (N.m)
1	238	9.8
2	255	8.11
3	272	7.42
4	289	5.31
5	306	4.01

5.2.1.2. Variable voltage torque analysis for helical gear train

In this analysis the voltage is varying while the current is taking constant.
The current is taking as 4 ampere throughout the process.

Table No. III Variable voltage torque analysis for helical gear train readings

Sr. no	Voltage (volt)	Output speed
1	70	190
2	75	250
3	80	304
4	85	454
5	90	628

Calculations: Given,
Current = 4amp
Power factor = 0.85
Hence,
Power (watts) = Current (amp)*Voltage (volt)*Power factor
Therefore,
Power (watts) = 2πNT/60
Where,
N = output speed (RPM)
T = Torque (N.m)
As per the calculations the torque is calculated as

Table No. IV Variable voltage torque analysis for helical gear train results

Sr no.	Power (kw)	Torque (N.m)
1	238	11.96
2	255	9.74
3	272	8.54
4	289	6.07
5	306	4.66

6 DISCUSSION

6.1 Numerical Analysis

6.1.1 Stress analysis of spur and helical gear train

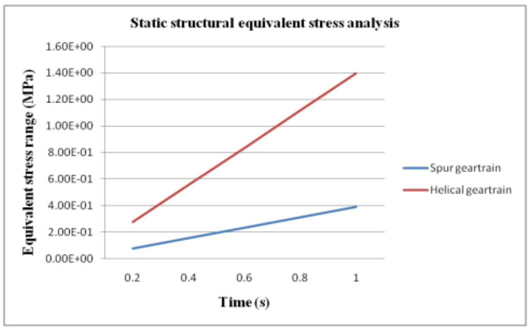

Fig. No. XII Stress analysis of spur and helical gear train

The graph above indicates the equivalent stress analysis which is obtained by numerical approach. As seen in the graph the spur gear train generates less stress in the gear train. But compared to helical the difference is not much and has increases as time interval increases. The spur is better for stress analysis. But helical can also shows better stress performance as the difference in both the gear train is less.

6.1.2 Total deformation analysis of spur and helical gear train

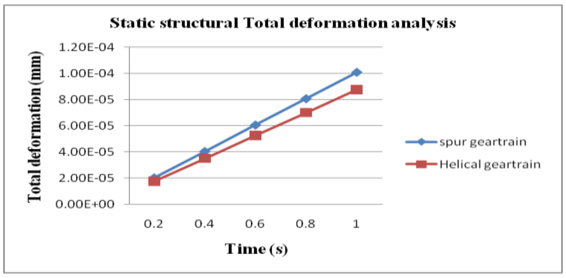

Fig. No. XIII Total deformation analysis of spur and helical gear train

The above graph indicates the total deformation behaviour of both gear trains. As shown in graph the total deformation is more for spur gear. Hence the helical gear here is more rigid for deformation. Therefore helical gear is better for total deformation analysis.

6.2 Experimental Analysis

The torque transmission capacity is investigated experimentally for both the gear trains, the results obtained for tests as variable voltage and variable loading as:

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6.2.1 Torque analysis for variable voltage with spur and helical gear

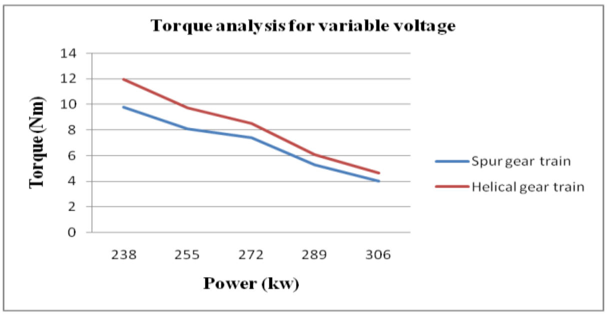

Fig. No. XIV Torque analysis for variable voltage with spur and helical gear

The graph above states that torque analysis for both gear train. As power increase, torque value is decreased. From above torque transmission capacity for variable voltage torque analysis test, helical gear train shows better performance compared to spur gear train.

7 CONCLUSION

The portal axle is the system which increases the ground clearance of the vehicle. It is mainly beneficial for off-road driving conditions. The 3D models of the two types of gear train developed by using the Pro-E software. ANSYS FEA software are able to predict the total stress analysis of both the gear train. Also the vibrational analysis of gear train is done with effective results. The total deformation in both the gear train is also analysed.

For that helical shows better results with less overall deformation on total unit.

For experimental analysis the torque transmission capacity of both the gear trains is calculated. The torque transmission is calculated by variable voltage. The helical gear shows better torque transmission capacity for portal axle unit.

Hence from both the numerical and experimental analysis the spur and helical gear train are compared. The helical gear train is better for total deformation and torque transmission analysis.

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