Topology Optimization of Automotive Gear using Fea

Mit Patel, Hadiya Valiulla, Vinay Khatod, Bhavin Chaudhary, Vikas Gondalia

***Abstract:** Gears are the key elements used to transmit power or motion from on shaft to another and it has wide range of applications. It's one of the major application is in the automobile gear box. Generally, gears fail when the working stress exceeds than the maximum permissible value. Here the generated stresses are directly in relation to amount power produced inside an engine, as well as also on torque. This study mainly focuses to identify the magnitude of the bending stresses generated in the selected gear set of CVT of a two-wheeler during power transmission as well as also tried to find different ways for reducing weight of the gear. Hence integrating the feature of topology optimization as a part of weight reduction over an existing part is considered as the key parameter of assessment for this work. In this study, gears of CVT gearbox of two-wheeler is analyzed for static loading under the application of tangential load resulting from maximum torque in the given application. After the study of the stress distribution on existing gears, the material removal area for weight reduction is identified on selected gears then the same study for stress distribution is carried out for proposed designs of topological optimization. Hence the both existing and proposed optimized designs are analyzed under static structural analysis for same loading and results for stress distribution are compared.*

Keywords: Bending Stress, CVT Gearbox, Tangential Load, Topology Optimization, Weight Reduction

I. INTRODUCTION

Gears are the most common means of transmitting power in the modern mechanical engineering world. They vary from a tiny size used in watches to the large gears used in watches to the large gears used in lifting mechanisms and speed reducers. They form vital elements of main and ancillary mechanisms in many machines such as automobiles, tractors, metal cutting machine tools etc. Toothed gears are used to change the speed and power ratio as well as direction between input and output.

Topology Optimization (TO) is a mathematical method that optimizes material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. TO is different from shape optimization and sizing optimization in the sense that the design can attain any shape within the design space, instead of dealing with predefined configurations. The conventional TO formulation uses a finite element method [FEM] to evaluate the design performance. The design is optimized using either gradient-based mathematical programming techniques such as the optimality criteria algorithm and the method of moving asymptotes or non-gradient-based algorithms such as genetic algorithms. Topology Optimization has a wide range of applications in aerospace, automotive, mechanical, bio-chemical and civil engineering etc. thus TO is a key part of design for additive manufacturing.

II. OBJECTIVE

1. As a part of designing of gears, there is still scope for research, especially when the performance is the main objective, with collected research data collected; it is noticeable that there is a scope to optimize gear geometry without affecting its strength.
2. Weight reduction provides much improved mechanical properties such as better strength to weight ratio, adequate hardness. Hence, less chances of failure.
3. Finite element analysis is viable approach to perform design optimization quickly as compared to solving complex partial differential equations.
4. Finite element approach can be utilized to identify stress and deformation in the gear geometry.
5. Optimizing the gear geometry by removing material from low stress regions can give improved design that can be beneficial for overall performance of the transmission system as well as better life of bearings and shafts.

III. DIMENSIONS, TERMINOLOGIES AND MATERIAL

This journal uses double-blind review process, which means that both the reviewer (s) and author (s) identities concealed from the reviewers, and vice versa, throughout the review process. All submitted manuscripts are reviewed by three reviewer one from India and rest two from overseas. There should be proper comments of the reviewers for the purpose of acceptance/ rejection. There should be minimum 01 to 02 week time window for it.

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A. *Dimensions and Terminologies*

Table- I: Parameters for Gear – 1

Gear – 1	Parameters / Dimensions
No. of Teeth	49
Tip Diameter (D_t)	75 mm
Pitch Circle Diameter (D)	71.44 mm
Module (D/T)	1.4580
Diametral Pitch (T/D)	0.686
Pressure Angle	20^0
Helix Angle	9.46^0
Addendum	1.4580 mm
Dedendum	1.8225 mm
Gear Width	18 mm
Clearance (Dedendum - Addendum)	0.3645 mm
Tooth Depth	4 mm

Table- II: Parameters for Gear – 2

Gear – 2	Parameters / Dimensions
No. of Teeth	51
Tip Diameter (D_t)	65 mm
Pitch Circle Diameter (D)	62.33 mm
Module (D/T)	1.22
Diametral Pitch (T/D)	0.8182
Pressure Angle	20^0
Helix Angle	15.26^0
Addendum	1.1961 mm
Dedendum	1.4952 mm
Gear Width	10 mm
Clearance (Dedendum - Addendum)	0.2991 mm
Tooth Depth	3 mm

B. Material Properties

As per the result of material testing, gear is made of material steel grade EN19. The selected gears of CVT gearbox are made of **EN 19 Grade Steel**, for which the specimens of gear 1 and 2 are tested via Positive Material Identification method. Material properties of EN19 steel are shown in below table:

Table- III: Material Properties

Density	7850 kg/m^3
Modulus of Elasticity	210 GPa
Poisson's Ratio	0.285
Yield Strength (sty)	555 MPa
Ultimate Strength (stu)	775 MPa

C. CVT Transmission Used in Automobile Vehicle

A Continuously Variable Transmission, or CVT, is a type of automatic transmission that provides more useable power, better fuel economy and a smoother driving experience than a traditional automatic transmission.

The CVT consists two variable-diameter pulleys each shaped like a pair of opposing cones that are split perpendicular to their axes of rotation, with a V-belt running between them. One pulley is connected to the engine (input shaft) and the other to the drive wheels via gear drives (output shaft). The halves of each pulley are movable; as the pulley halves come closer together, the belt is forced to ride higher on the pulley, effectively making the pulley's diameter larger. Changing the diameter of the pulleys varies the transmission's ratio. The gear ratio is changed by moving the two halves of one pulley closer together and the two halves of the other pulley farther apart. The V-shaped cross section of the belt causes it to ride higher on one pulley and lower on the other. This changes the effective diameters of both pulleys, which changes the overall gear ratio. As the distance between the pulleys and the length of the belt does not change both pulleys must be adjusted (one bigger, the other smaller) simultaneously in order to maintain the proper amount of tension on the belt.

D. CAD Modeling and Finite Element Analysis of Existing Gearbox

From the existing model of CVT Gearbox of Honda Activa, the basic required dimensions are measured and then the 3D-CAD model is prepared of same dimension in SolidWorks 2016*64 Edition. The simulation is based on boundary conditions and loads to be applied on gears in ANSYS 17.0. The structural analysis is then used to determine the Von Mises stresses and total deformation in the gears.

- Geometry of Existing Gear Design

Basic Dimensions of the gear 1 and 2 are measured from the actual gear models and CAD model is created through reverse engineering.

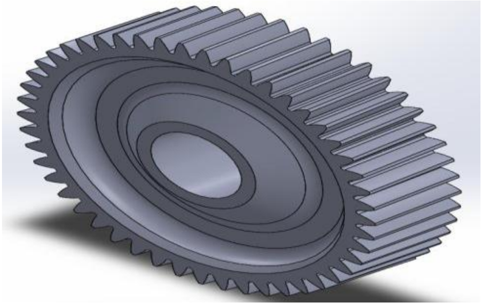

Fig. 1 CAD Model of Gear - 1

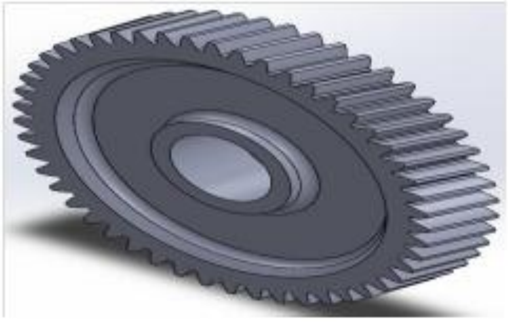

Fig. 2 CAD Model of Gear - 2

- Boundary Conditions and Application of Load

The CAD models of gear 1 and 2 are meshed into finite element model using tetrahedron mesh element is used and then applying boundary conditions for further static structural analysis such as Apply displacement at center and also apply tangential force of value at tooth of gear 1 resulting from maximum torque (9 N-m) as shown in figure. Further Stresses on the gears are observed and confirmed to be within the permissible limit of 555 MPa.

- FEA Analysis of Gears

Both gears are analyzed considering the above mentioned boundary conditions as well as loading conditions.

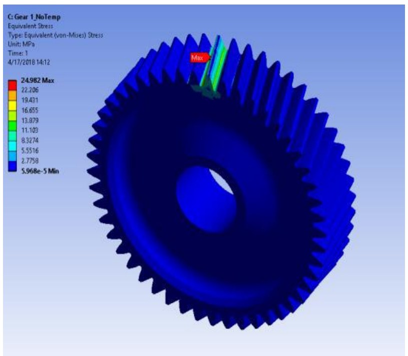

Fig. 3. Plot of Equivalent Stress for Gear – 1

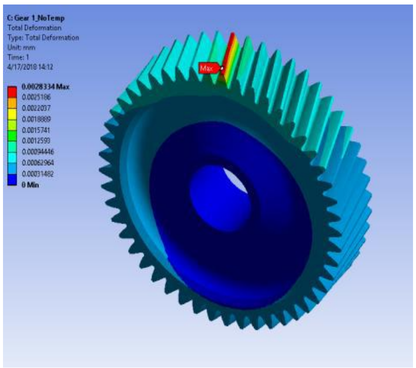

Fig. 4. Plot of Total Deflection for Gear – 1

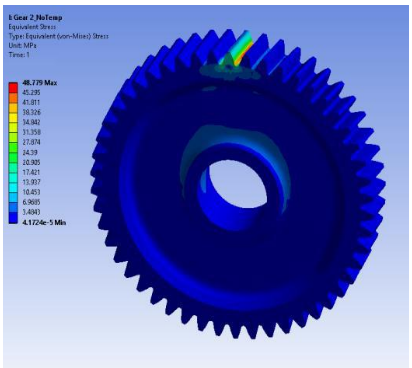

Fig. 5. Plot of Equivalent Stress for Gear – 2

The stress and deformation values found from the FEA analysis for existing gears that the stress value for both gear 1 and 2 are within the permissible limit of 555 MPa. Hence from the analytical value it is evident that still there is a possibility to optimize gear geometries by removing material from its side surface without affecting its strength.

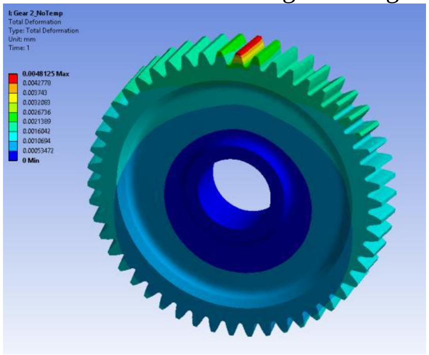

Fig. 6. Plot of Total Deflection for Gear – 2

IV. TOPOLOGY OPTIMIZATION

A. Proposed Topology Optimizations and FEA for Gear – 1 Final Drive

Fig. 7 Circular Cut

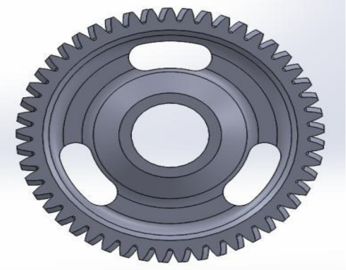

Fig. 8 Obround Cut (3 Slots)

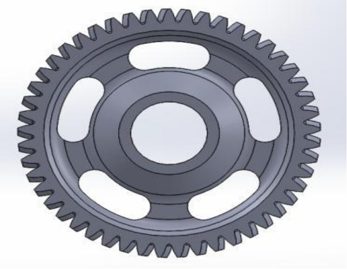

Fig. 9 Obround Cut (6 Slots)

Here, the above figures indicates the proposed designs optimization as by providing holes on a side face of a gear 1. where, figure 7: Scenario 1 - Circular cut on side face of a gear of 8 mm diameter, figure 8: Scenario 2 - Obround cut on side face of a gear of 3.5 mm diameter of curvature with arc length of 30° (3 Slots) and figure 9 Scenario 3 - Obround cut on side face of a gear of 3.5 mm diameter of curvature with arc length of 30° (6 Slots).

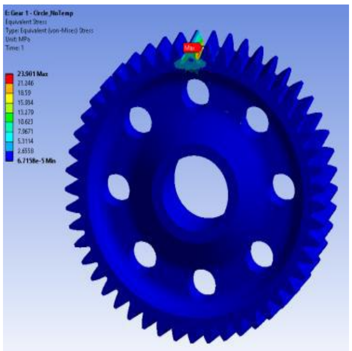

Fig. 9 VMS Scenario – 1

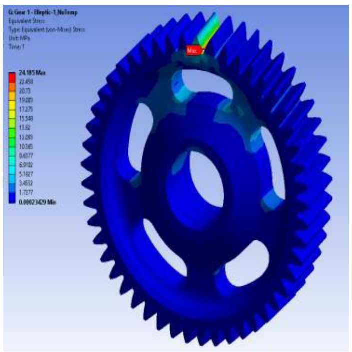

Fig. 10 VMS Scenario – 2

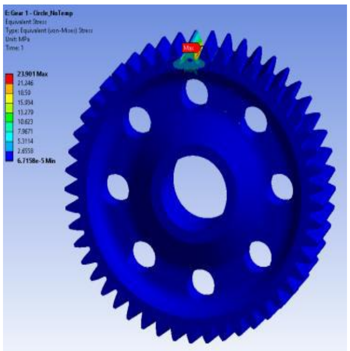

Fig. 11 VMS Scenario – 3

Here, (VMS* - Von Mises Stress) the above figures 10, 11 and 12 indicates the equivalent Von Mises Stress for all 3 proposed design optimizations (Scenario1, 2 and 3), where stress observed in the existing gear 1 is much less than the permissible limit of 555 MPa.

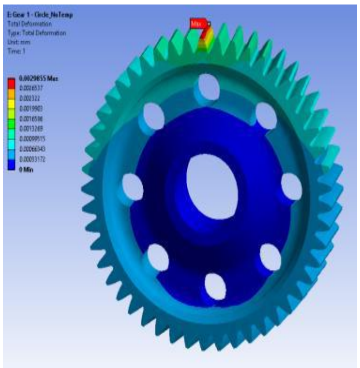

Fig. 12 TD Scenario – 1

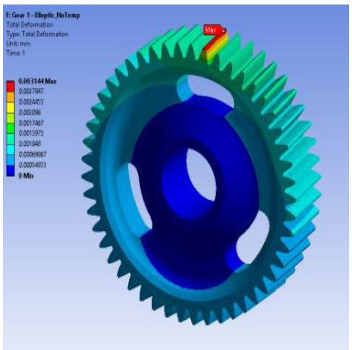

Fig. 13 TD Scenario – 2

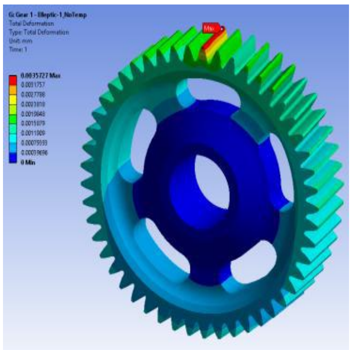

Fig. 14 TD Scenario – 3

B. Proposed Topology Optimizations and FEA for Gear – 2 Counter Gear

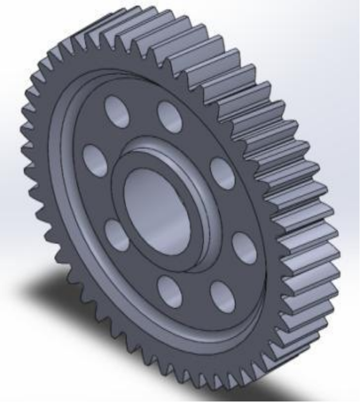

Fig. 15 Circular Cut

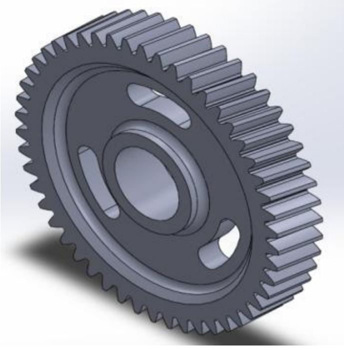

Fig. 16 Obround Cut (3 Slots)

Fig. 17 Obround Cut (6 Slots)

Similarly as above, here the above figures indicates the proposed designs optimization as by providing holes on a side face of a gear 2.

where, figure 16: Scenario 1 - Circular cut on side face of a gear of 8 mm diameter, figure 17: Scenario 2 - Obround cut on side face of a gear of 3.5 mm diameter of curvature with arc length of 30° (3 Slots) and figure 18: Scenario 3 - Obround cut on side face of a gear of 3.5 mm diameter of curvature with arc length of 30° (6 Slots).

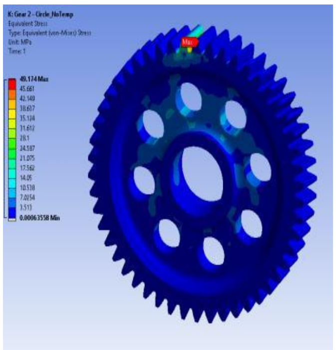

Fig. 18 VMS Scenario - 1

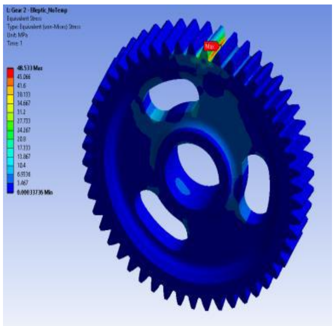

Fig. 20 VMS Scenario – 2

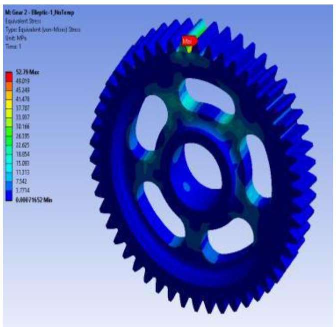

Fig. 19 VMS Scenario – 3

Here, (VMS* - Von Mises Stress) the above figures 19, 20 and 21 indicates the equivalent Von Mises Stress for all 3 proposed design optimizations (Scenario1, 2 and 3), where stress observed in the existing gear 2 is much less than the permissible limit of 555 MPa.

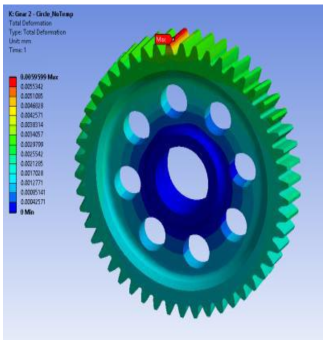

Fig. 20 TD Scenario – 1

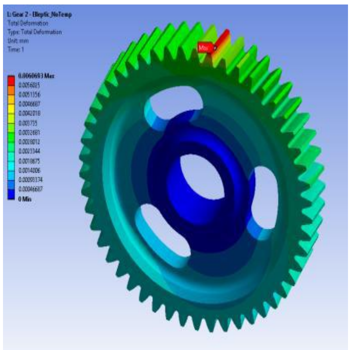

Fig. 21 TD Scenario – 2

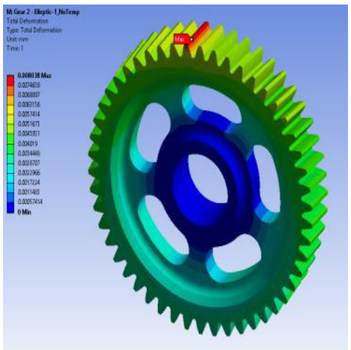

Fig. 22 TD Scenario – 3

Here, (TD* - Total Deformation) the above figures 22, 23 and 24 indicates the total deformation for all 3 proposed design optimizations (Scenario1, 2 and 3), where the deformation is within the safe limit.

V. RESULT AND DISCUSSION

It is seemed from the below mentioned comparative results between existing design and optimized design that, there is remarkable weight reduction is possible on gear 1 and 2 under the application of static loading without much affecting the functionality of the gear and keeping the stresses within the acceptable limit.

Table IV Stress Value and Total Deformation for Proposed Optimization: Gear - 1

Gear	Proposed Optimization	Stress Value (MPa)	Total Deflection (mm)
Gear – 1	Circular Holes	23.901	0.0029855
	Obround Holes (3 Slots)	24.544	0.0031440
	Obround Holes (6 Slots)	24.185	0.0035727

Table V Stress Value and Total Deformation for Proposed Optimization: Gear - 2

Gear	Proposed Optimization	Stress Value (MPa)	Total Deflection (mm)
Gear – 2	Circular Holes	49.174	0.0059599
	Obround Holes (3 Slots)	48.533	0.0060693
	Obround Holes (6 Slots)	52.790	0.0080380

Hence for practical assessment and experimental work, the scenario 1 is implemented for both gears (gear 1 and 2) through machining via radial drilling operation on radial drilling machine as shown in fig.25.

Fig. 25 Gear – 1 & 2: After Machining Implementation of scenario 1 for both

Table VI Weight Comparison for both gears

Gear	Weight of Existing Gear (kg)	Weight of Optimized Gear (kg)	% Weight Reduction
Gear – 1: Final Drive	0.76	0.72	5.2%
Gear – 2: Counter Gear	0.16	0.14	12.5%

This paper represents a general view of mass optimization of helical gears under static loading condition. It represents finite element analysis method for the helical gear tooth using ANSYS 17. The helical gears are studied for actual loading conditions as in the vehicle, and then under the same loading condition the different geometries are studied. Hence the results represents that, it is possible to reduce the weight of these gears without much increase in stresses and keeping the functionality of gears intact.

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