FEA & OPTIMISATION OF STEERING KNUCKLE OF ATV

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Abstract — Steering Knuckle is a non-standard component linking the suspension, steering & braking systems and the wheel hub to the chassis of a vehicle. This study aims to redesign the steering knuckle in order to reduce the unsprung weight of a single seat All Terrain Vehicle (ATV) while retaining a satisfactory safety factor for better performance of the vehicle. A two step process has been used for the same. First step is modeling the knuckle as per the structural considerations and design constraints set by suspension, steering and brake assemblies & determination of loads acting on the knuckle. The second step is stress analysis using finite element software and design adjustments for reducing weight without compromising on the structural strength. According to the analysis results, material can be added to parts that are subjected to higher stress than the safety factor permits. Material can also be removed from low stress areas, thus, helping to reduce the component weight.

Keywords—Steering Knuckle; ATV; Finite Element Analysis (FEA); Weight Reduction; Optimisation.

I. INTRODUCTION

Mass or weight reduction is becoming a core highlighted issue in automobile manufacturing industry to improve fuel efficiency thereby reducing emissions. Weight reduction has been achieved through advances in materials, improved design and analysis methods, fabrication processes and optimization techniques, etc. Design optimization should be implemented to obtain a minimum weight with maximum or feasible performance, based on removal of conflicting constraints, design boundaries, and design uncertainties, such as design clearance and material defects.

The steering knuckle on a vehicle is a joint that allows the steering arm to turn the front wheels. It is the connection between the tie rod, stub axle and axle housing. [6] Steering knuckle is connected to the axle housing by using king pin. Another end is connected to the tie rod. The wheel hub is fixed over the knuckle using a bearing. The function of the steering knuckle is to convert linear motion of the tie rod into angular motion of the stub axle. A knuckle design is dependent on the suspension, brake and steering subassembly design of the particular vehicle and hence gives flexibility to optimize it in terms of weight and durability. Inspite of the large design variations, steering knuckles are divided into two main types - with a hub or with a spindle. [3] Among the vehicle structural components, the knuckle is one of the important parts in the suspension system. A reduction in the weight of suspension components also improves the vehicle’s handling performance. It plays a crucial role in minimizing the vertical and roll motion of the vehicle body when it is driven on a rough road. A knuckle component is required to support the load and torque induced by bumping, braking, and acceleration and also helps in steering the tire connecting tie rod and rotating at the kingpin’s axis centre. Under operating condition it is subjected to dynamic forces transmitted from strut and wheel. Steering Knuckle is subjected to time varying loads during its service life which may lead to fatigue failure. The steering knuckle accounts for maximum amount of weight of all suspension components, which expedites the necessity of weight reduction. In the design optimization of the knuckle component, weight should be minimized, while design factors such as strength, stiffness and durability should be satisfied with design targets. An effective design is one which performs the required task efficiently and is safe under extreme operating conditions, while being economical in the material used as well as the manufacturing process needed yet having an aesthetic appeal. Analysis aids in understanding the behavior of a component under a particular loading cycle for both failures and redundancies. Therefore analysis gives us a mathematical model which indicates scope for optimization and weight reduction for an overdesigned component.

II. LITERATURE REVIEW

For a design optimization of steering knuckle it is necessary to look into the design aspects and literature available in order to better understand the
need of the industry for weight reduction of components and to establish the increasing role of FEA as a tool for the same. The literature available has increased multifold over the past decade and multiple forms of design structures, FEA methods and optimization techniques have emerged.

Thomas Gillespie in ‘Fundamentals of Vehicle Dynamics’ attributes the necessity of a sound design to the fact that the imperfections in the manufacturing of tires, wheels, hubs, brakes and steering knuckle of the rotating assembly results in non uniformities like mass imbalance, dimensional variations and stiffness variations. These non-uniformities cause variations in the forces and moments at the ground. He further elaborates that the cornering behavior is an important performance mode and is equated with the responsiveness of a vehicle to driver input, or the ease of control. Author also explains the steering geometry and the forces experienced during cornering. He also elaborates the front wheel geometry and the forces and torques to be considered while designing a steering system.

Mehrdad Zoroufi and Ali Fatemi of the University of Toledo compared properties of different materials used for manufacturing of steering knuckle. For cast aluminum and cast iron knuckles, since the material properties are less dependent on geometrical orientation, the specimens were taken from the hub and one of the arms, respectively. It was observed that cast aluminum and cast iron reach 42% and 54% of the forged steel yield strength, respectively, and 37% and 57% of forged steel ultimate tensile strength, respectively. The percent elongation, as a measure of ductility, for the cast aluminum and cast iron was 24% and 48% of the forged steel, respectively. This indicated that forged steel was superior in strength as compared to cast iron and cast aluminum. Furthermore, in producing the forged steel steering knuckle more recycled material was used than in producing the other steering knuckles.

In ‘An Introduction to Modern Vehicle Design’, Julian Happian-Smith enlists the principle requirements of a steering and suspension mounting as:

- To provide good ride and handling performance
- To ensure that steering control is maintained during maneuvering
- To ensure that the vehicle responds favorably to control forces produced by the tires as a result of longitudinal braking and accelerating forces, lateral cornering forces and braking and accelerating torques
- To provide isolation from high frequency vibration arising from tyre excitation

Julian Happian-Smith further states that vehicle designs are affected by the reduced development times dictated by market forces; i.e. components need to be designed quickly with a minimum of rig and vehicle testing prior to launch. Consequently considerable emphasis is placed on computer-aided design requiring the use of multi-body systems analysis software. This software enables many ‘what-if’ scenarios to be tested quickly without the need for a lot of development testing, but they do require sophisticated mathematical models to be developed for various components and sub-systems. There are also other limitations such as cost, weight, packaging space, requirements for robustness and reliability, together with manufacturing, assembly and maintenance constraints to be considered while design and optimization process.

In the book ‘The Finite Element Method: Its Basis and Fundamentals’, Zeinkiewicz, Taylor and Zhu explain the concepts behind the mathematical modeling of component under study with emphasis on the mesh generation and mesh relevance parameters. Their work is a skeletal structure on which the FEA method for the steering knuckle optimization was developed.

III. COMPARISON OF MANUFACTURING PROCESS OF KNUCKLE

A. Casting

The knuckle almost always has a complex geometry. Therefore casting is the best suited manufacturing process for these complicated shapes. Casting apart from being economical for mass production also imparts good damping characteristics to the component. The disadvantages are poor surface finish, internal surface defects such as cracks, pores and blowholes.

B. Forging

Forged components exhibit higher strength as compared to cast or machined components due to strain hardening. Forging uses the highest percentages of recycled steel, thus reducing the material cost. However warping of the components is possible during cooling of the component. Also heavy and effective machinery is needed for forging. Hence it is a costly process. Knuckles of high performance cars etc. are manufactured using forging. [10]

C. Block Machining

In block machining an entire block of box dimensions is taken and the knuckle is manufactured from the block using a machine like VMC. Block machining imparts high strength to the component. Also extremely good surface finish and highly accurate dimensional tolerances can be obtained in this process. In this process the raw material wastage is highest. It is used only when the number of required components is less and casting and forging is uneconomical for the required number of components. [10]
IV. ANALYSIS OF FORCES ACTING ON THE KNUCKLE

The forces acting on the knuckle and the points of application of the forces are very important in the Finite Element Analysis study. As the geometrical and physical constraints of every vehicle are different, there is no standard range of values for forces acting on the knuckle. For this study the following data is considered for the study of forces acting on the knuckle of a track car. The forces, calculated in Newton, are converted to G – Forces by dividing with the weight of the car to present a standardized value which can then be compared to forces acting on the knuckles of other vehicles.

**TABLE I. DATA FROM ATV DESIGN (TEAM PIRAHNA RACING)** [12]

<table>
<thead>
<tr>
<th>Mass</th>
<th>m</th>
<th>400 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Distribution</td>
<td>W.D.</td>
<td>50:50</td>
</tr>
<tr>
<td>Turning Radius</td>
<td>R</td>
<td>8 m</td>
</tr>
<tr>
<td>Wheeltrack</td>
<td>C</td>
<td>1016 mm</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>B</td>
<td>1524 mm</td>
</tr>
<tr>
<td>Height of C.G.</td>
<td>H</td>
<td>559 mm</td>
</tr>
<tr>
<td>Velocity</td>
<td>V</td>
<td>40 km/hr</td>
</tr>
<tr>
<td>Suspension Spring Stiffness</td>
<td>K</td>
<td>25 N/mm</td>
</tr>
<tr>
<td>Suspension Max. Travel on Bump</td>
<td>X</td>
<td>101.6 mm</td>
</tr>
<tr>
<td>Steering Wheel Input Force</td>
<td>F_a</td>
<td>60 N</td>
</tr>
<tr>
<td>Steering Gearbox Ratio</td>
<td>G</td>
<td>12</td>
</tr>
<tr>
<td>Lateral Acceleration During Turn</td>
<td>A_l</td>
<td>15.43 m/s²</td>
</tr>
<tr>
<td>Pedal Force</td>
<td>P</td>
<td>294.3 N</td>
</tr>
<tr>
<td>Area of TMC Piston (Dia=19.05 MM)</td>
<td>A_t</td>
<td>284.2 mm²</td>
</tr>
<tr>
<td>Area of Caliper Piston (Dia=24.55 MM)</td>
<td>A_c</td>
<td>506.7 mm²</td>
</tr>
<tr>
<td>No. Of Caliper Pistons</td>
<td>N</td>
<td>2</td>
</tr>
<tr>
<td>Coeff. Of Friction Between Pad And Disc</td>
<td>μ</td>
<td>0.45</td>
</tr>
<tr>
<td>Deceleration On Braking</td>
<td>a_d</td>
<td>7 m/s²</td>
</tr>
</tbody>
</table>

**TABLE II. MATERIAL USED FOR STUDY** [9]

<table>
<thead>
<tr>
<th>Alloy Steel 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
</tr>
</tbody>
</table>

The forces acting on a knuckle are:

**A. Lateral Force due to Turning**

Lateral force or side force is the cornering force produced by a vehicle tyre during cornering. It is equivalent to the centrifugal force generated due to cornering.

**B. Brake Force due to Torque Required for Braking**

Brake force is generated on the knuckle at the points of brake caliper mountings when brake is applied to retard the motion of the vehicle. It is calculated as the product of the pressure generated in fluid line with net area of caliper pads and the coefficient of friction between the brake pads and the brake disc.

**C. Force due to Steering Gearbox During Turning**

This is the force exerted by the steering gearbox on the steering arm mounting of the knuckle through the tie rod while turning.

**D. Weight Transfer During Breaking or Turning**

During acceleration and braking, inertia of the vehicle chassis causes a load transfer in longitudinal direction on the vehicle; i.e. the load form the rear is transferred to the front while braking and the opposite effect takes place while accelerating. This load transfer (or weight transfer) exerts a force on the knuckle. A similar effect takes place while negotiating a corner. Inertia causes load transfer in lateral direction; i.e. the load form the right side is transferred to the left side while taking a right turn and vice versa.

**E. Bump Force**

When the vehicle undergoes a ground disturbance in the form of a bump or a hole a force is exerted on the knuckle. For design considerations, it is assumed that the suspension spring has attained full travel which is 4 inches. [12][1][4]

**F. Force on Impact**

When the vehicle is subjected to a front, rear or side impact an impulse force is exerted on the knuckle. For this study purpose, this force has been neglected as it is ambiguous to predict the nature of such impact force. [5]

**TABLE III. FORCE VALUES CALCULATED FOR GIVEN DATA**

| Lateral Force Due To Turning | 3085.8 N | 3.14G |
| Brake Force Due To Torque Required For Braking | 2360.86 N | 2.41G |
| Force Due To Steering Gearbox During Turning | 720 N | 0.367G |
| Longitudinal Load Transfer | 102.03 N (Force = 26.17% Load Transfer) | 1.05G |
| Lateral Load Transfer | 3395.8 N (Force = 86.53% Load Transfer) | 3.46G |
| Bump Force | 2540 N | 2.59G |
| Force On Impact | NEGLIGED |
V. FINITE ELEMENT ANALYSIS

Finite Element Analysis is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations by subdivision of a whole problem domain into simpler parts, called finite elements. Variational methods from the calculus of variations are used to solve the problem by minimizing an associated error function. FEA as applied in engineering is a computational tool for performing engineering analysis. It includes the use of mesh generation techniques for dividing a complex problem into small elements, as well as the use of software program coded with FEM algorithm. In applying FEA, the complex problem is usually a physical system with the underlying physics such as the Euler-Bernoulli beam equation, the heat equation, or the Navier-Stokes equations expressed in either PDE or integral equations, while the divided small elements of the complex problem represent different areas in the physical system.

Meshing is the process of converting a solid body into an assortment of nodes and elements. Nodes are singular points on the body of the component. Geometrical entities created by joining of nodes are called elements. All required calculations by the software are made at the nodes. The values obtained at nodes are interpolated throughout the entire element. For example for a quad element the interpolation function is:

\[ u = a_0 + a_1 x + a_2 y + a_3 xy \]  

VI. METHODOLOGY

A. Solid Modeling, Meshing and FEA

A knuckle was designed for the calculated loads, taking all the mounting points and bearing surfaces as critical points. The material was considered to be Alloy Steel EN24. The solid modeling was done in SOLIDWORKS. The weight of the knuckle was 2.544 kg. Stress and Displacement Analysis is performed on the knuckle by applying the various loads calculated in the previous section. Loads are applied in singular as well as in combination to simulate real-time road conditions. The analysis was done using Altair HYPERMESH. The solver used was Radioss V12. Maximum Stress was found out to be 90 MPa. Hence the factor of safety (FOS) is 5.99. This shows that the component is over designed providing ample scope for weight reduction without affecting the structural strength and integrity. The displacement analysis shows that maximum displacement in the component is 0.018 mm or 18 microns which is well within limits.

The Boundary conditions for a FEA problem are basically the points of application of the constraints as well as the forces on the knuckle. The boundary conditions depend mostly on the geometry of the knuckle. Generally the suspension mountings are constrained as they are in direct contact with the chassis of the vehicle. The lateral forces for the FEA model are applied to the bearing support step provided in the knuckle. The forces due to braking are applied at the brake mounting points and forces due to steering gearbox are applied on the steering arm bolting points. The bump force is applied on the top half of the bearing surface. Accurate application of loads, moments and constraints is important for proper analysis results.
D. Optimisation for Weight Reduction

The model of the knuckle is over designed. Hence Weight Optimization study was done. The software used for weight optimization is solidTHINK INSPIRE V9. Keeping the same magnitude of loads and identical loading conditions the result obtained shows the parts of the knuckle from where the material can be removed without disturbance of internal stress flow patterns within the material. This result was taken as reference and a new revised design of the knuckle was created. The material was Alloy Steel EN24 and the solid modeling was done in SOLIDWORKS. The weight of the new revised knuckle was found out to be 947 g. This design was once again meshed and analysis was performed in ANSYS.

Due to the reduction in the volume of the component there is significant reduction in the weight. The maximum stress induced in the component is higher than the original model; i.e. 327 MPa but it is still within the limits of the yield strength of the material.

Hence the Max Stress was 327 MPa which gives a factor of safety of 2.05. Hence even though there is significant weight reduction the design is safe. The maximum displacement was 0.080 mm i.e. 80 microns which is acceptable.
used. The factor of safety achieved is sufficient to absorb the forces of impact which have been neglected in this study. Hence it is safe to conclude that the optimized design is safe for operation.

2) There was no attempt to create a mathematical model for the front, rear and side impact of the vehicle and hence this component of the force was neglected while doing the analysis.

3) The manufacturing process required for the revised design is complex as compared to the original model. Hence the cost of manufacturing will be more.

4) No comparative study was done with respect to the cost of manufacturing.

**B. Future Scope of Study**

5) The analysis performed is static structural analysis, hence for further improvement of the component, fatigue analysis should also be considered.

6) Similar to the steering knuckle, many other automobile components can be subjected to FEA and Optimization study to reduce weight, cost and materials.

Thus we conclude that FEA of steering knuckle plays a very important role in the design procedure of the wheel assembly of the vehicle. It can be seen that there is major scope in weight reduction of the vehicle by reducing the weight of the steering knuckle using FEA techniques.

**REFERENCES**


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**RESULT AND CONCLUSION**

The knuckle created initially was overdesigned. Hence it was optimized for weight reduction. The revised design showed a 62.78% reduction in weight and 62.95% reduction in material volume as compared to the initial design; while having a factor of safety of 2.05. Thus we can conclude that it is a safe design. Maximum stress and displacement are within control parameters / limits. The optimization process gives a small change on the displacement. It means that change of volume and shapes does not significantly influence the stiffness of the structure. Therefore, the overall weight of the vehicle can be reduced to achieve savings in costs and materials, as well as, improve fuel efficiency and reduce carbon emissions. The unsprung mass of the vehicle is reduced by 6.4kg which will contribute to improved vehicle handling.

**A. Limitations of the Study**

1) Forces were considered to be acting in ideal conditions which does not happen in practical application.