Design cycle implementation on a customized steering knuckle for a competition ATV

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Abstract. The design cycle in its most basic terms can be defined as investigate, plan, create and evaluate. It has been adopted by every engineering team in its own way to strengthen the intended design. The crucial factor of any mechanical design is consideration of service loads for components proposed function. This paper talks about the implementation of the design cycle on three iterations of a customized steering knuckle for BAJA SAE India competition. Effect of terrain and road profiles on vehicle along with conventional knuckle design process is highlighted. The authors outline the criteria and limitations of knuckle design for a competition and discuss the first design and its performance and failures, failure analysis and how the lessons learnt were incorporated in the second design. The design cycle was revisited for optimization resulting in a third design. Finally, the optimized design steering knuckle was fabricated and tested in actual terrain of the competition for validation.

Keywords: Design cycle, steering knuckle, ATV, failure analysis, SAE BAJA

1. Introduction
BAJA SAEINDIA is an intercollegiate design competition run by Society of Automotive Engineers (SAE) in India. The objective of the event is to design, build, fabricate and validate an All-terrain vehicle (ATV). Teams from various colleges build an ATV as shown in Figure 1 and run it in the competition held at National Automotive Testing R&D Infrastructure Project (NATRIP) facility, Pithampur, Indore. An ATV is a typical mini off road vehicle powered by a 10hp gasoline engine. These vehicles take part in series of events. The vehicle is tested for engineering practices, agility and durability.

The performance of vehicle is verified by events like suspension test, maneuverability test, acceleration test, brake test and endurance event. The objective of these events is that the vehicle has to successfully complete all the events in least time. The vehicle experiences irregular terrain like ditches, bumps, sharp corners, table top, roll over and 6-8 feet drops. Hence various parts of the vehicle fail due to over loading, impact forces and manufacturing defects. The parts prone to frequent failures are drive axles, tie rods, steering knuckle, ball joint, A-arms and trailing arms. Steering knuckle is the most critical component of the vehicle which takes up all the forces from the wheel and transfers to the various components of the vehicle [1]. If the steering knuckle fails or is damaged, the vehicle becomes immobile and entire knuckle has to be replaced to run the vehicle once again, so proper analysis of the
The knuckle is mandatory. The design objective of the knuckle is that it must be equally strong and lightweight. Weight reduction is one of the important factors in the automobile industry since less weight implies a more efficient product. The knuckle consists of various points like suspension mounting point, steering arm, stub axle and brake caliper. The functions of the knuckle are to hold the weight of the vehicle, to transmit the force from the wheel to the suspension system, to hold brake calliper and to convert linear motion of steering tie rod to angular motion. The knuckle connects the wheels of the vehicle to the chassis and a bearing attached to the stub axle of knuckle is connected to wheel hub as shown in Figure 2. The parts that are mounted on knuckle are brake calliper, tie rod and A-arms. The functionality of the steering knuckle enables it to undergo dynamic and impact forces regularly in the terrain. The dynamic and impact force analyses becomes essential for any team to design and fabricate customized steering knuckle.

1. Literature survey

Many researchers have worked on analysis of the steering knuckle. Sanjay Yadav et al. [1] concentrated on weight reduction aspect of a conventional steering knuckle through different materials under static loads. Tagade et al. [2] emphasized on optimization of steering knuckle by reducing the weight and comparing the cast iron and aluminum material. Purushottam Dumber et al. [3] have proposed a modified design of a steering knuckle over a conventional design by keeping the maximum stresses and displacements almost same in both the models, but reducing the weight by 11%. S V Dusane et al. [4] has stated steering knuckle as critical and stress sustaining part of an ATV. The author has carried out static and modal analysis on spindle and knuckle separately of a customized steering knuckle by considered load on spindle, braking force, torque and steering arm force. Author recommended the Aluminum 6061-T6 alloy for the given ATV achieving minimum weight with adequate strength. S. Vijayarangan et al. [5, 6] claimed a new Aluminum Metal matrix composite developed by them has shown better performance compared to conventional spheroidal graphite (SG) iron applied to conventional steering knuckle under both static and fatigue loads. The results thus helped them to attain 55% of weight saving compared to SG iron. Mehrdad Zoroufi et al. [7] have conducted specimen test, FE analysis and component test on steering knuckle for different materials under fatigue loads. The authors claim forged steel knuckle is stronger compared to cast Aluminum knuckle, but at the expense of weight. As per the existing knowledge at present, literature on consideration of static, dynamic and impact analysis on customized steering knuckle is unavailable. As for an ATV the road conditions are uneven, the authors believe that the calculation of these forces and its effect on customized steering knuckle becomes essential. In this paper authors expand on an initial knuckle design, lessons learnt from running the vehicle at the competition and propose a design cycle adopted to design and build an optimized steering knuckle of an ATV for SAE BAJA competition.

![Figure 1. SAE Baja vehicle](image1)

![Figure 2. Front Wheel Assembly](image2)
2. Design Methodology
The design methodology adopted for the steering knuckle is shown in Figure 3. The design objective of the steering knuckle was to reach minimum weight without affecting its functionality. The geometry of the knuckle depends mainly on the suspension points. The initial design was made by taking coordinate input from Optimum Kinematics software. The input such as wheelbase, track width, weight distribution, longitudinal CG distance, CG height, etc. which are defined by the rules of the competition were fed to the Optimum Kinematics software to obtain the suspension and steering coordinate points. These coordinate points serve as basic input for deciding the shape of the steering knuckle. The shape of the steering knuckle has been derived on the basis of frugal material usage, simple design and ease of fabrication. The CAD model of the steering knuckle was prepared in Solid works 2016. The location of the brake caliper mount on the steering knuckle was decided on the basis of maximum clearance available from the rim and wheel hub. The final CAD model thus has a steering knuckle integrated along with brake caliper mount. The steering knuckle model was analyzed for both static and dynamic loads in ANSYS Workbench 15.0. Elimination of sharp corners and sudden geometry change in the steering knuckle was done in order to reduce stress concentration effect. Once the CAD model of steering knuckle was confirmed, the model was then 3D printed and was incorporated in the wheel assembly of the vehicle to check the physical fitment, clearances and tolerance. Since the objective was to attain minimum weight of steering knuckle, the material Aluminum 6061-T6 alloy was selected [4].

![Design cycle adopted for steering knuckle](image)

2.1. Early testing
After fitment confirmation the steering knuckle was thus fabricated and installed in the vehicle, which is followed by performance evaluation of the steering knuckle on the testing track. The behaviour of the steering knuckle was observed at certain intervals of the testing and found it undamaged throughout the test, indicating acceptable design methodology and fabrication. Though the test results were satisfactory for steering knuckle, one of the steering knuckles (left steering knuckle) in actual event failed. After ensuring no manufacturing defect in the steering knuckle fabrication, one of the knuckles failure lead to doubt about accuracy of calculations. The following section emphasizes on failure analysis of the failed steering knuckle.

2.2. Failure analysis
Failure occurred during endurance test of the competition. In this test, the ATV should complete maximum laps in a span of 4 hours by overcoming ditches, bumps, sharp corners, table top, water bed, etc. present on the track. To achieve maximum laps, the ATV was driven at a speed of 40 km/h (maximum speed), however at critical junctures; speed was reduced to 25 km/h. The steering knuckle
broke when the front left wheel of the vehicle passed an elongated ditch and experienced a sudden load while coming out of it at a speed of 40 km/h. The failed section of left steering knuckle has been shown in Figure 4. The initial impression of the failure was overload or faulty fabrication of the component. But by thorough analysis of the nature and texture of the failed surface area along with the circumstances in which the steering knuckle broke led to the conclusion that impact analysis in design cycle was not analysed to its fullest and was the reason for failure. This led to redesigning of the steering knuckle by considering the various loading patterns in combination with impact loads.

### 3. Designing of modified steering knuckle

Through Finite Element (FE) analysis for the calculated impact force, steering knuckle was showing more than allowable stress at the same failed critical section. Even the common observation was that ailed cross section was the least available cross section in the whole steering knuckle. Hence the redesigning of the steering knuckle had become essential by taking the static, dynamic along with impact loads. Thus the steering knuckle was modified by imbibing the new inputs from real off-road terrain and the lessons learnt from previous event into consideration. Based on these considerations, a modified steering knuckle was modeled and is shown in Figure 5.

#### 3.1. Loading considerations

The forces acting on the steering knuckle was identified based on the terrain in which the ATV travels. The steering knuckle experiences forces such as steering force, bump force, cornering force, weight transfer, impact force and brake torque. These forces are calculated by set of formulae [6, 8] available in the literature.

| S.no. | Parameters        | Magnitude       |
|-------|-------------------|-----------------|
| 1     | Steering force    | 220N            |
| 2     | Brake torque      | 218N-m          |
| 3     | Bump force        | 3479N           |
| 4     | Load transfer     | 1146N           |
| 5     | Cornering force   | 4279N           |
| 6     | Impact force      | 4634N(t=0.3sec) |

For the calculations, some input parameters were considered like the weight of the ATV with driver as 250kg, maximum velocity of 40kmph, tire radius as 10 inch, wheel base as 54 inch and turning radius.
as 2m. Table 1 show the magnitude of loads at different cases and the magnitude of impact force is 4634N, which is greater than the other forces indicating the significance of the impact force in the analysis.

By considering the terrain, the ATV performance and life is mainly depended upon the impact resistance of the each component. Since the steering knuckle takes up all the forces from wheel and transfers to the various parts of ATV, it must have adequate strength in static, dynamic and impact. After the terrain was properly examined for the possible load conditions on the steering knuckle, three possible scenarios were found out by which the component could fail. The loads acting on the steering knuckle along with its magnitude in these cases are mentioned in the Table 2. For simplicity these scenarios are being referred to dynamic, dynamic with lateral impact and dynamic with vertical impact conditions. These severe conditions cover most of the forces coming on steering knuckle at different maneuvering of an ATV.

Table 2. Load conditions experienced by steering knuckle

| Sl. No | Practical scenario | Loads | Magnitude | Condition       |
|-------|--------------------|-------|-----------|-----------------|
| 1     | Vehicle going in a ditch while taking a corner | Steering force | 220N | Dynamic          |
|       |                    | Cornering force | 4279N |                 |
|       |                    | Load transfer   | 1146N |                 |
|       |                    | Brake torque    | 218N-m|                 |
|       |                    | Bump force      | 3479N |                 |
| 2     | Vehicle going in a ditch while taking a corner and having an impact after hitting an obstacle | Steering force | 220N | Dynamic with lateral impact |
|       |                    | Cornering force | 4279N |                 |
|       |                    | Load transfer   | 1146N |                 |
|       |                    | Brake torque    | 218N-m|                 |
|       |                    | Bump force      | 3479N |                 |
|       |                    | Lateral impact  | 4634N |                 |
| 3     | Vehicle going in a ditch while taking a corner and having an impact after hitting an obstacle | Steering force | 220N | Dynamic with vertical impact |
|       |                    | Cornering force | 4279N |                 |
|       |                    | Load transfer   | 1146N |                 |
|       |                    | Brake torque    | 218N-m|                 |
|       |                    | Bump force      | 3479N |                 |
|       |                    | Vertical impact | 4634N |                 |

Table 3. Properties of AA 6061-T6 material

| AA 6061-T6 | Properties |
|------------|------------|
|            | Density (Kg/m³) | Young’s modulus (GPa) | Poisson’s ratio | Yield strength (MPa) | Ultimate strength (MPa) |
|            | 2700 | 68.9 | 0.3 | 276 | 310 |
3.2. Material selection
Several materials are used for steering knuckle like Cast iron, EN8, AA 6061-T6, etc. The material selected for the modified steering knuckle was based on parameters such as density, yield strength, cost, availability and ease in machining. Since AA 6061-T6 exhibits better strength to weight ratio resulting in greater weight reduction of the component, it was chosen as material for the component. The mechanical properties are mentioned in the Table 3.

4. Finite element (FE) analysis
In this section, the analysis on modified steering knuckle for various load conditions(Table 2) is discussed. FE analysis has been carried out in ANSYS Workbench 15.0. This section basically involves meshing of the modified steering knuckle model and defining the appropriate boundary conditions.

4.1. Meshing
The meshing was done for element size of 1mm, 2mm, 3mm, 4mm and 5 mm by considering tetrahedron and hex dominant element types. The results were compared among different element type and size. Mesh control was done by giving refinement on critical areas. The number of nodes and elements are 13,25,313 and 3,67,920 respectively for 1mm Hex dominant element. The number of nodes and elements 3,03,648 are 1,83,526 respectively for 1mm Tetrahedron element. The mesh of the steering knuckle is shown in the Figure 6 and Figure 7.

| Boundary Type       | Location                  | Direction                  |
|---------------------|---------------------------|----------------------------|
| Fixed Support       | Suspension pivot points   | -                          |
| Bump force          | Stub axle                 | Vertically upwards         |
| Steering force      | Steering arm              | Lateral(towards the wheels)|
| Brake torque        | Calliper mount            | Clockwise                  |
| Cornering force     | Stub axle                 | Lateral(towards the wheels)|
| Weight transfer     | Stub axle                 | Vertically downwards       |
| Vertical Impact force| Stub axle                 | Vertically upwards         |
| Lateral Impact force| Steering arm              | Lateral(towards the wheels)|

Figure 6. Hex dominant Mesh
Figure 7. Tetrahedron Mesh
4.2. Boundary conditions
The boundary condition involves force location and magnitude along with line of action on different regions of the modified steering knuckle. The restraints and forces on certain nodes of different regions of modified steering knuckle are given in Table 4. These forces line of actions are derived based on its connectivity to the other components and function. For example, bump force exerted from wheel from the road bump is transferred to the stub axle vertically upwards of the steering knuckle. This vertically upward force on steering knuckle necessarily generates bending force and a direct force in it.

Figure 8 shows the various boundary conditions in dynamic analysis of modified steering knuckle. The forces acting in this condition are steering force, bump force, cornering force, weight transfer and brake torque. The magnitude and direction of the forces are visible in Figure 8 and is same as mentioned in Table 2 and Table 4. The Figure 9 shows the boundary condition in dynamic with vertical impact analysis of modified steering knuckle. The forces acting in this condition are same as dynamic condition but an extra vertical impact force is added in this condition. Similarly the Figure 10 has an extra lateral impact force in the analysis. The magnitude and direction of these extra forces are same as mentioned in Table 2 and Table 4.

5. Results and Discussion
It is observed that impact analysis is a significant factor in the design methodology of the steering knuckle. The dynamic analysis in combination with impact analysis was carried out considering the real scenarios. The results were then compared for element types and element sizes. The graph of
stress vs. element size and deformation vs. element size for both tetrahedron and hex dominant element type in all the conditions mentioned in Table 2. Though the convergence has obtained for element size 3mm with respect to total deformation within industry acceptable limits (less than 10% error between two successive analyses), the von-Mises stress have converged for an element size of 1mm and for hex dominant element. Thus for further analyses hex dominant element with 1mm element size has been chosen.

The von-Mises stress distribution (for hex dominant element with size 1mm) in the modified steering knuckle for all three conditions is shown in Figure 11 to Figure 14. The vertical forces in dynamic and dynamic with vertical impact analysis (Figure 11 and Figure 12) are dominating to produce the maximum bending effect in the stub axle of modified steering knuckle. The point on the stub axle away from the wheel experiences highest bending moment i.e. at the joining point of stub axle to centre body. In dynamic and dynamic with vertical impact analysis, the maximum von-Mises stress was 64.94 Mpa and 124.93 Mpa respectively, at the stub axle juncture. By considering the vertical impact force in the analysis induced an increased stress of 93.75%. This vertical impact found to be severe at the stub axle juncture and its contribution to induce stress rise is visible.

Figure 11. Von-Mises stress Dynamic analysis

Figure 12. Von-Mises stress for Vertical impact analysis

Figure 13. von-Mises stress lateral impact analysis

Figure 14. Von-Mises stress for Lateral and vertical impact along with dynamic analysis

Figure 13 shows the maximum von-Mises stress was found to be 142.37 Mpa at the joining point of steering arm and centre body. The lateral impact force acts as eccentric load at this steering arm juncture leading to the maximum bending moment. From the above study, the critical regions were identified to be stub axle and steering arm juncture. In the failed steering knuckle, the steering arm was
broken which also indicates that steering arm is a critical region and implying that it is the weakest region in the steering knuckle. To further validate the critical region of the steering knuckle, an analysis of modified steering knuckle under the loading condition of dynamic, vertical and lateral impact force applied all together. The maximum von-Mises stress of 161.29MPa was found at the steering arm juncture, at the same critical region in the steering knuckle as shown in Figure 14.

Table 5. von-Mises stress and FOS values of all the three analysis

| Analyses Type                                      | Von-Mises stress (Mpa) | FOS |
|---------------------------------------------------|------------------------|-----|
| Dynamic                                           | 64.94                  | 4.25|
| Dynamic with vertical                             | 124.93                 | 2.20|
| Dynamic with lateral                              | 142.37                 | 1.93|
| Dynamic with lateral and impact analysis           | 161.29                 | 1.71|

A comparison of factor of safety (FOS) is each of these analyses is given in Table 5. According to the Table 5, the steering knuckle will be safe for worst design scenario’s considered in the analyses. The standard steering knuckle (Original Equipment Manufacturer) made up of cast iron weighed 2.4kg. The customized steering knuckle built weighed 0.6 kg, achieving a weight reduction of 1.8kg for single steering knuckle. The overall weight reduction for two steering knuckles is 3.6kg leading to potential for improvement in the performance of the ATV.

6. Optimisation

With focus on optimisation the modified steering knuckle was evaluated and it was observed that the cantilever section for steering arm and upper and lower suspension arms needed to be properly supported for continuous operation in extreme conditions. Further it was realised that with application of Anti-Ackerman geometry the turning radius of the vehicle can be further reduced. The existing design had regular Ackerman geometry. Revisiting the design cycle and following the steps detailed in above sections led to an optimised knuckle as shown in Figure 15. Figure 16 shows the FE analyses for worst load condition resulting in maximum stress of 195.06 Mpa (FOS = 1.4) indicating a safe design.

**Figure 15.** CAD model of Optimised knuckle

**Figure 16.** FE analysis for Optimised knuckle
7. Conclusions

Design cycle was proposed and followed to develop a customized steering knuckle of an ATV. This cycle enabled the authors to analyze the cause of failure in an earlier steering knuckle and thus guided in proper failure analysis. An optimized steering knuckle was modeled and analyzed for the real scenarios of the terrain and competition. The physical fitment assurance of the 3D printed model was satisfactory and fabricated by using AA6061-T6 as shown in Figure 17. The optimized steering knuckle was used at the competition as shown in Figure 18 and successfully completed all the events validating the design. The following are the major observations made during the design process.

- Impact analysis plays a crucial role in the designing of modified steering knuckle.
- Through the FE analysis, steering arm was found to be critical region of the steering knuckle.
- The design objective of having the least possible weight without sacrificing functionality was achieved.

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