Design Analysis and Optimization of Steering Knuckle Using Numerical Methods and Design of Experiments

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***Abstract* - A most important issue in vehicle industry is the existence of differences in the physical properties and manufacturing methodologies. Deterministic approaches are incapable to take into account these variabilities without leading to oversized structures. The necessity of assessing the robustness of a particular design requires a methodology based on strength and design optimization through probabilistic models of design variables (DOE). In general it is identified the steering knuckle which is one of the critical components of vehicle which links suspension, steering system, wheel hub and brake to the chassis. In this paper I have identified the above problem the process of optimizing the design using a methodology based on durability and design optimization through probabilistic models of design variables (DOE).**

***Index Terms*-- Knuckle, Optimization, DOE**

I. INTRODUCTION

A Steering Knuckle is one of the critical components of vehicle which connects brake, suspension, wheel hub and steering system to the chassis. It undergoes varying loads subjected to different circumstances, while not distressing vehicle steering performance and other desired vehicle characteristics. The knuckle is the major pivot in the steering mechanism of a car or other vehicle, free to revolve on a on single axis. The knuckle is vital component that delivers all the forces generated at the Tier to the chassis by means of the suspension system. The design of the knuckle is usually done considering the various forces acting on it which involves all the forces generated by the road reaction on the wheel when the vehicle is in motion. The design also includes various constraints that are related to the knuckle such as brake system, steering system, drive train and suspension system. Knuckle is an important part on the car, its main function is to load and steering, which support the body weight, transfer switch to withstand the front brake torque and braking torque so on. Therefore, the shape of the structure and mechanical properties knuckle, there are strict requirements. The project deals with creation of geometric model of steering knuckle (LUV) in solid works after that that model will be imported to NFX Nastran for finite element modelling where the meshing properties , element properties will be generated. Loads and model conditions applied to model there by generating .nas file that file will be submitted to solver (Nastran) and linear static structural analysis will be performed. To conduct model analysis to understand the dynamic behavior of the structure and thereby followed by transient structural response analysis. Then in the post processing analysis input and output parameters will be listed down after that Design of Experiments process will be done from that by getting response surface the results of it will be used for optimization. If it gives does not give desired results in the optimization point of view then again linear static structural analysis, model analysis and transient structural response analysis be done till we get desired results keeping input and output parameters same for every iteration under the same DOE and response surface.

II. LITERATURE REVIEW

The life of a vehicle is strongly ascertained by its components' fatigue life. Inconsistency in the material parameters (such as Young's modulus and tensile strength) may strongly affect the fatigue life. This paper contains demonstration related to vehicle knuckle structure. Firstly, a probabilistic approach to determining fatigue life is figured out to examine the reliability of vehicle fatigue predictions in the presence of material variability. [3]

By reducing mass of the vehicle components, overall mass reduction of a vehicle and lowering of energy consumption demand can be achieved, therefore, improving fuel efficiency. Material resources will also be conserved. The objective of this research is to reduce mass of an existing steering knuckle component of a local car model by applying shape optimization technique. The improved design helps attain 8.4% mass reduction. Although volume reduction and shape changes exist, there is no significant change in maximum stress. This result is satisfactory with optimization in shape only, limited design space and no design change in material properties. [4]

A systematic approach to tolerance synthesis includes considering the manufacturing cost as a function of tolerance. A prime step in product development is allocation of manufacturing and design tolerances. This paper focuses on the optimal solution of the least cost tolerance design. The modified exponential cost tolerance model has been considered. The SA-PS algorithm, a non-traditional global optimization technique, has been adopted as the solution for its internal advantages.

III. MODELING AND ANALYSIS OF STEERING KNUCKLE

Steering knuckle model of light utility vehicle (LUV) is modeled in solid works with existing dimension. This model is further used for process of optimization. The forces acting on the steering knuckle are due to forces created the tire due to static or dynamic conditions when vehicle is stationary or in running conditions. Analysis of steering knuckle is done in Midas NFX for these forces which are acting on it. Forces are due to static load of vehicle, steering effort, breaking force (Moment force) and due to constraints of the vehicle. Cad model created in solid works in imported into Midas NFX for analysis.

IV. IMPLEMENTATION

Phase 1

- It is a pre-processing phase
- Creation steering knuckle Geometry
- Finite Element Modelling (Meshing)
- Materials & element properties
- Load and boundary conditions under static and dynamic conditions

Phase 2

- It is a processing phase

Knuckle will be subjected to static and dynamic load conditions where I will be performing linear static structural analysis, model analysis (Frequency or Eigen value), Transient structural response analysis and the critical parameters of knuckle affecting the response will be listed down for design of experiments considering manufacturability.

Phase 3

- Post processing and Design of Experiments using Methodology mentioned below

1. State the objective of the study.
2. Determine the response parameters(s) of interest that can be measured.
3. Determine the controllable factors of interest that might affect the response parameters and the levels of each factor to be used in the experiment. It is better to include more factors in the design than to exclude factors, that is, prejudging them to be non significant.
4. Determine the uncontrollable parameters that might affect the response parameters, blocking the known nuisance parameters and randomizing the runs to protect against unknown nuisance variables.
5. 5. Determine the total number of runs in the experiment, ideally using estimates of variability, precision required, size of effects expected, etc., but more likely based on available time and resources.
6. Design the experiment, remembering to randomize the runs.
7. Perform the experiment according to the experimental design, including the initial setup for each run in a physical experiment.

- Visualization of results and (methodology)

Phase 4

- OPTIMIZATION

From the second and third phases I will collect all the input parameters affecting the output parameters and there by generating the Response surface and there by generating the optimized model.

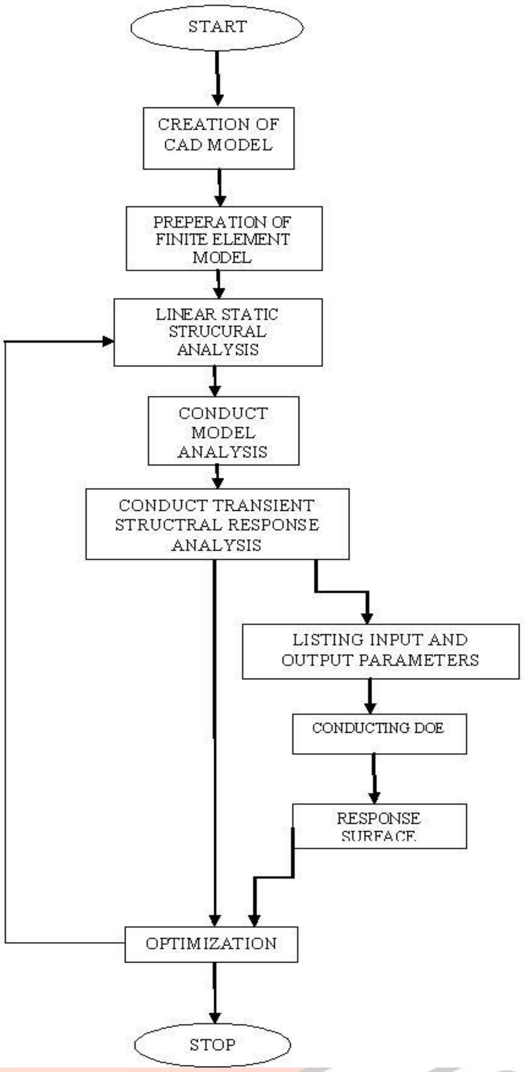


Figure 1: Design Optimization Flowchart

V. MODELING AND ANALYSIS OF STEERING KNUCKLE

To observe maximum stress produce into steering knuckle, model is subjected to intense circumstances and static analysis is carried out in Midas NFX. Steering force from tie rod to steering knuckle is calculated and applied to knuckle with its self weight. A combined load of braking force and lateral acceleration were applied to the model considering the longitudinal load transfer during braking and lateral load transfer during cornering as shown in table below.

Table 1: Loading Conditions [2]

Braking Force	1.5*g
Lateral Force	1.5*g
Steering Force	Steering effort of 50 N
Load on knuckle hub in X-Direction	3*g
Load on knuckle hub in Y-Direction	3*g
Load on knuckle hub in Z-Direction	1*g

Table 2: Mesh statistics

NUMBER OF NODES	29642
NUMBER OF ELEMENTS	18460
NUMBER OF DOFS	88926
NUMBER OF EQUATIONS	85317

There are two types of load acting on knuckle i.e. force and moment This knuckle is designed for vehicle of 2960 kg so breaking force acting on it produces moment: Moment = force* perpendicular distance

= 1.5*g *78Nmm
= 1.5*(2960/4)*10*78
= 865800 Nmm

Table 3: Loading conditions for knuckle

LOADING CONDITIONS		Load
Braking Force	1.5*g	22200
Lateral Force	1.5*g	22200
Steering Force	Steering effort of 5	50N
Load on knuckle hub in X-Direct	3*g	22200
Load on knuckle hub in Y-Direct	3*g	22200
Load on knuckle hub in Z-Direc	1*g	7400

VI. STATIC & DYNAMIC ANALYSIS OF STEERING KNUCKLE

A. STATIC ANALYSIS

Name	Gray Cast Iron	
Type	Isotropic	
Color	🟨	
Structural	Elastic Modulus	6.61780e+004
	Poisson's Ratio	2.70000e-001
	Coefficient	1.20000e-005
	Mass Density	7.20000e-006
	Ref. Temperature	0.00000e+000
Thermal	Conductivity	4.50000e-002
	Specific Heat	5.10000e+002
	Heat Gen.Factor	1.00000e+000
Factor of Safety Calculation	Failure Theory	Von Mises Stress (Ductile)
	Tension	1.51660e+002
	Compression	5.72160e+002
Damping Factors	Mass Proportional Damping	0.00000e+000
	Stiffness Proportional Damping	0.00000e+000
	Structural Damping Coefficient	0.00000e+000

Figure 2: Analysis Case

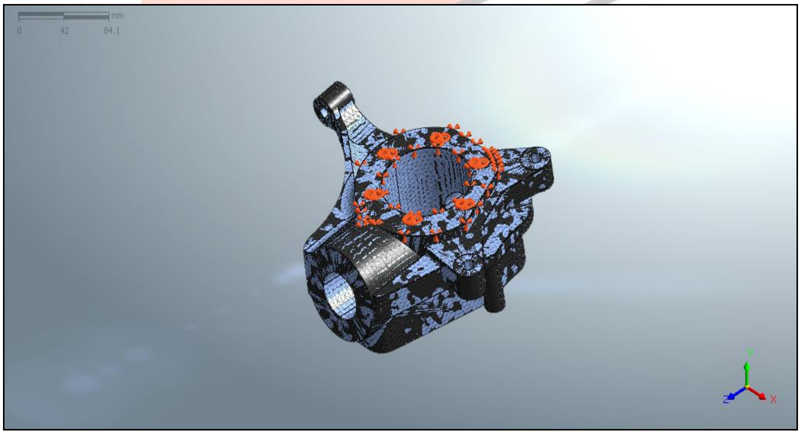


Figure 3: Boundary Label (FIXED)

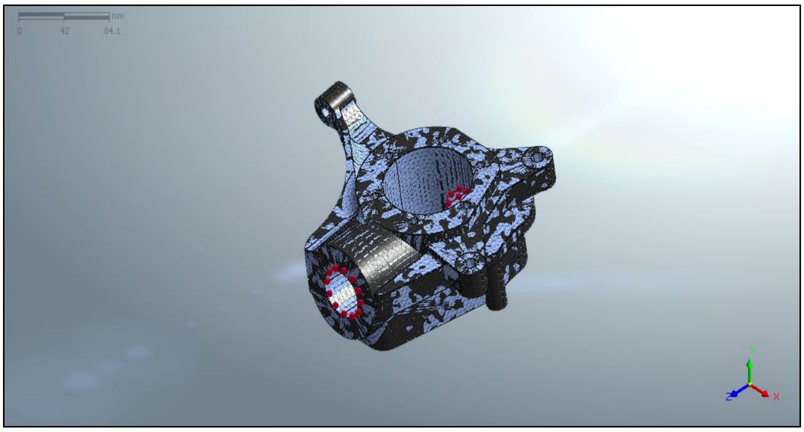


Figure 4: Static Load Label (STATIC)

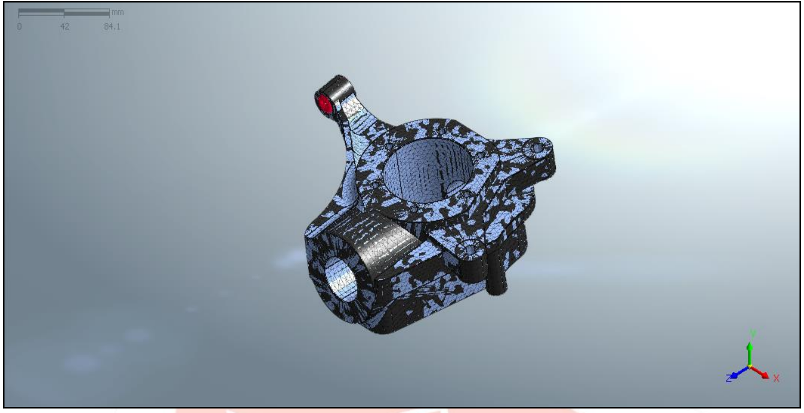


Figure 5: Static Load Label (steering)

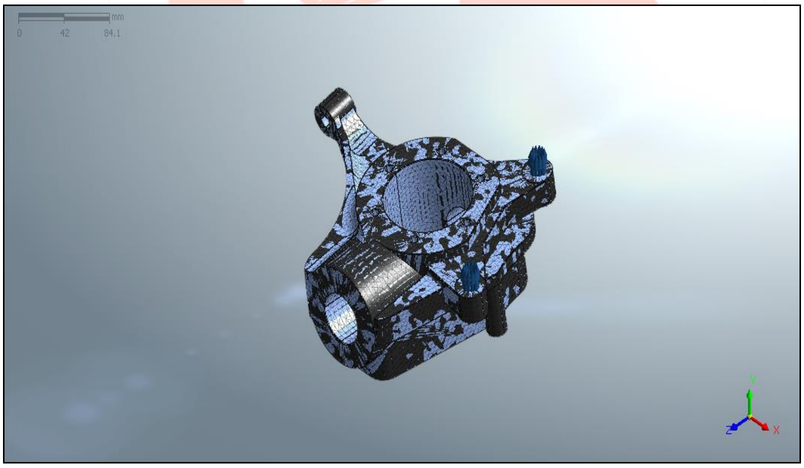


Figure 6: Static Load Label (moment)

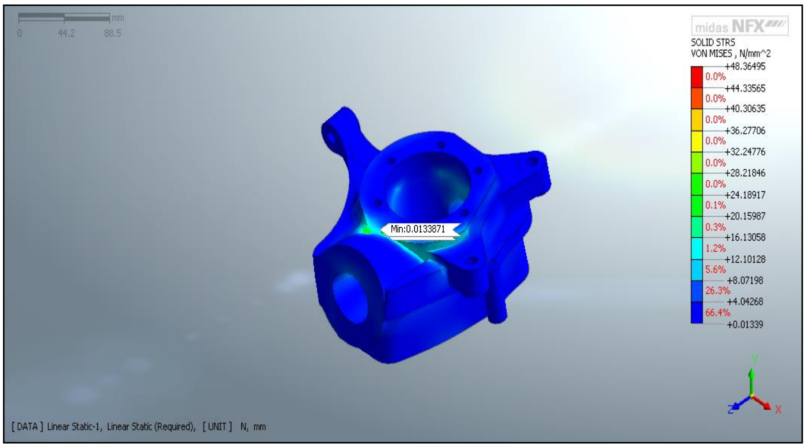


Figure 7: SOLID STRS VON MISES

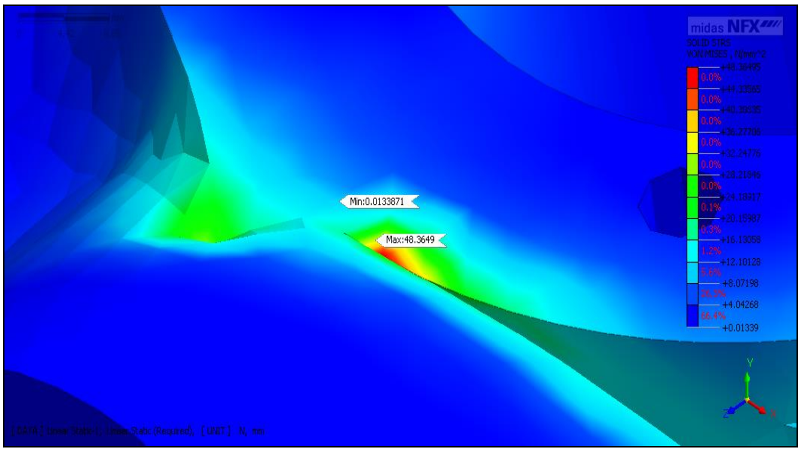


Figure 8: SOLID STRS VON MISES (Max: Max: 4.83649e+001)

Table 4: Max/Min Solid Safety Factor

Result Type	Element ID-Pos.	Safety Factor
MaxFactor of Safety Calculation	184-Center	1.15747e+004
MinFactor of Safety Calculation	61911-Center	3.13574e+000

B. DYNAMIC ANALYSIS

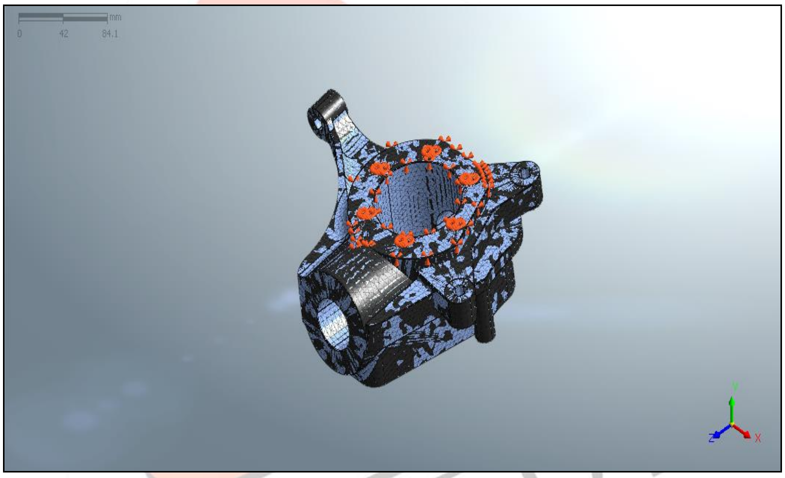
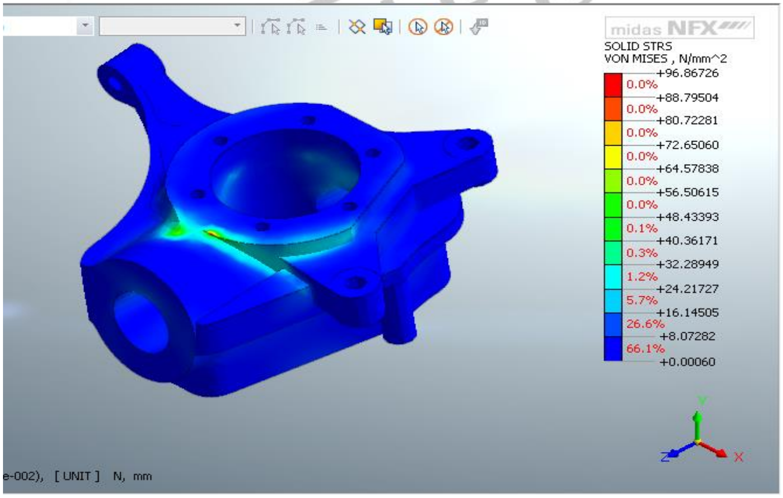


Figure 9: Boundary Label (Boundary Set-1)



Picture 10: SOLID STRS VON MISES

Figure 11: SOLID STRS VON MISES (Max: 0.00000e+000)

VII. TOPOLOGY OPTIMIZATION

Conventionally, these decisions are made by designer’s personal experience, intuition and usually an existing design. And the final design will come after a long and tedious “trial-error” process. However this design process limits the design space to the experience and creativity of the designer. Time and resource are lost in the Iteration to cut out all the failed designs.However cost, manufacturing time, ergonomics and many other important factors are not considered. It is obviously not what a designer is searching for in the modern world. We can see that “optimization driven design” process replace the time consuming “trial - error” iteration with optimization block. In which topology optimization is used in concept level to propose a material layout based on precise design requirements and constraints. By proposing the concept layout, FEA optimization can help designers to make useful design decision and reduce significantly the design process towards the optimal product.

VIII. DESIGN OF EXPERIMENTS & ANALYSIS

Table 5: Parameters to be changed for optimization

		Value	Lower boundary value	Upper boundary value
P1	**Figure.11.1**	20	18	22
P2	**Figure.11.2**	28	24	28
P3	**Figure.11.3**	60	56	60
P4	**Figure.11.4**	65	61	65

Above parameters will be changed in actual model and to get diff combinations of 81DOE models. Form these 81 DOE models graph will be generated which is called as response surface from that design parameter to be changed will be decided to get the optimized model.

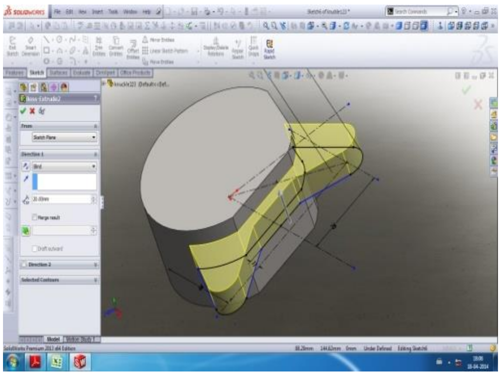


Figure 11.1 Parameter P1

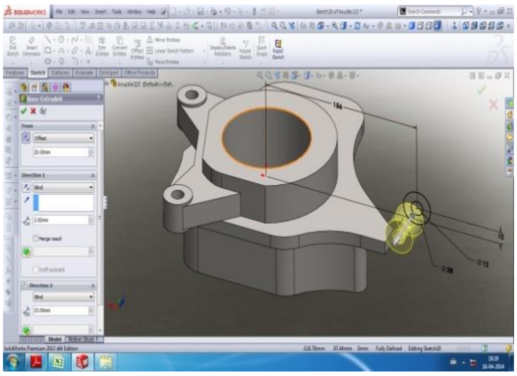


Figure 11.2 Parameter P2

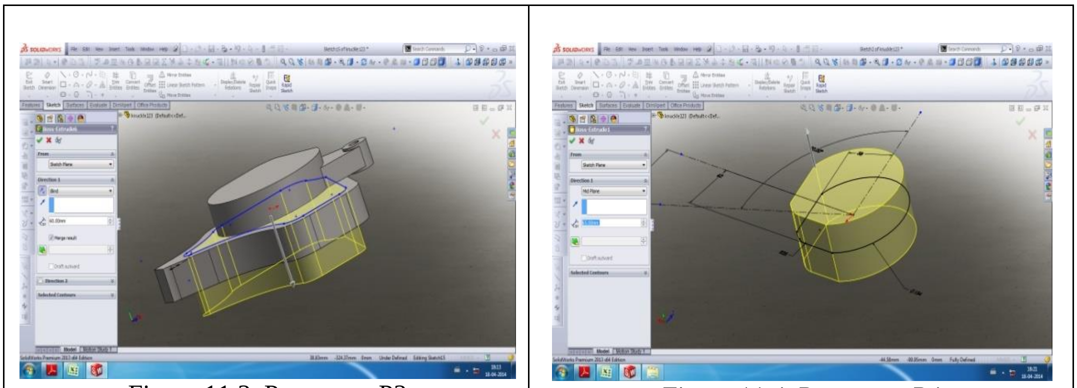


Figure 11.3 Parameter P3

Figure 11.4 Parameter P4

Figure 13: Parameters to be changed

Table 6: Description of Parameters

Short Name	Long Name	Unit	Lover Values	Upper Value	Values
P1	Flange	mm	18	22	5
P2	moment load location thickness	mm	24	28	5
P3	bearing hole hub thickness	mm	56	60	5
P4	hub thickness	mm	61	65	5

IX. RESULTS AND DISCUSSIONS

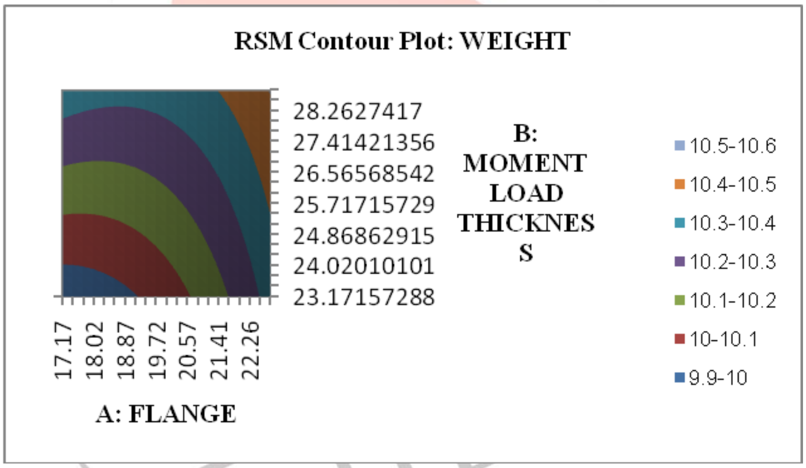


Figure 14: RSM Contour Plot: WEIGHT

Above graph shows variation of different parameters which in result gives different weights of the knuckle for every different design of experiment.

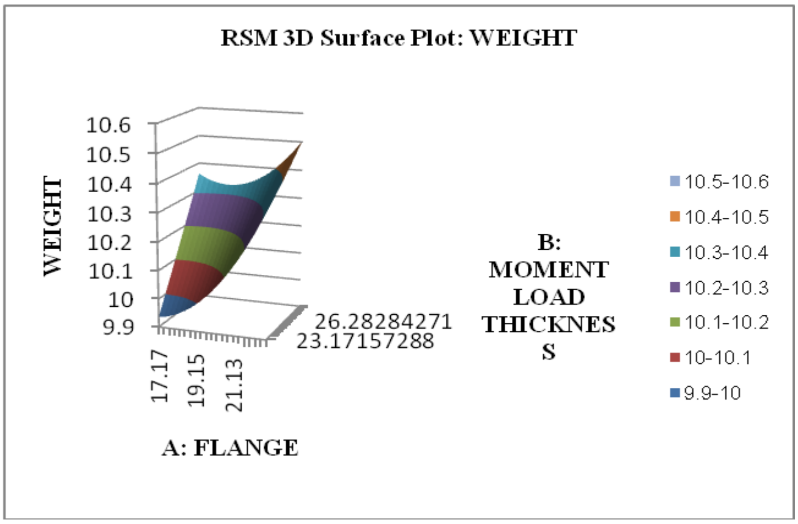
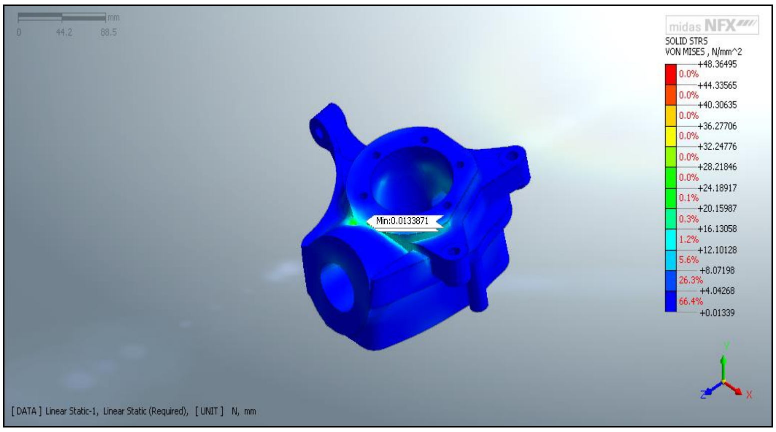
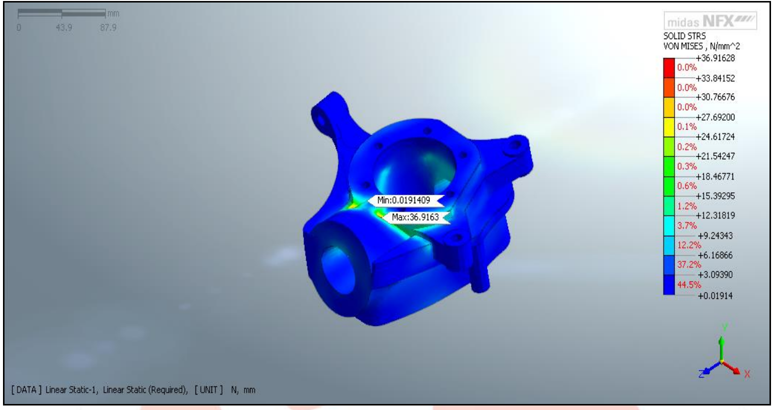


Figure 15: RSM 3D Surface Plot: WEIGHT

Figure 15 shows response surface generated due to various design of experiments which gives optimized value of weight with reduced overall weight and stress on knuckle.



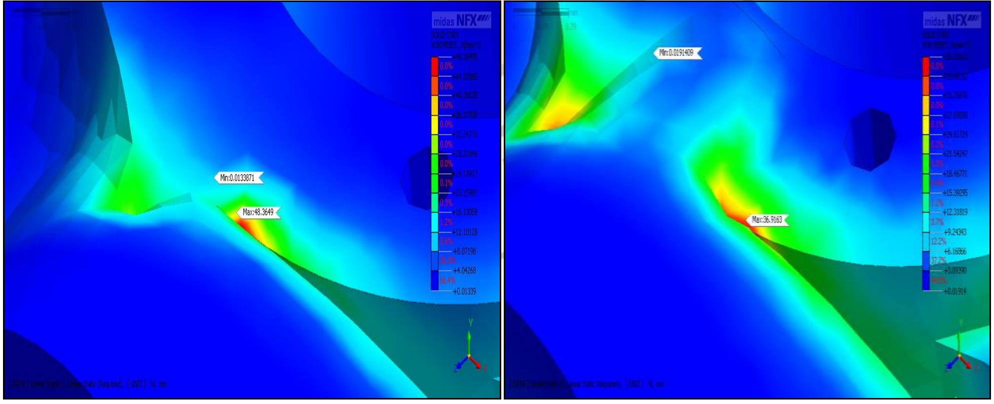
Original model



Optimized model

Figure 16: Original Model stress V/s Optimized model stress

Static stress



Original Model **Optimized model**

Figure 17: Original Model stress V/s Optimized model [static & dynamic stress]

Table 7: Optimization Results

	ORIGINAL DESIGN	OPTIMIZED DESIGN	% REDUCTION
MASS[Kg]	**10.9025**	**9.9**	**9.195%**
STRESS[MPa]	**48.3649**	**36.9163**	**23.67%**
DISPLACEMENT[mm]	**0.02387**	**0.02646**	**-**

X. CONCLUSIONS

When optimized model is compared with initial model, 9.195% Reduction in weight has been achieved with stress and deflection change within range and not exceeding above the Project target limits.

XI. FUTURE SCOPE

Other vehicle components also can be optimized so that to have less overall vehicle weight in similar way also when there will be change in material of knuckle significantly more mass reduction can be achieved by keeping stress and deflection values within control limits.

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