Modal Analysis, Fatigue Analysis and Optimization of Pitman Arm Using FEM

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***Abstract*— Steering system is used to steer the front wheels corresponding to the inputs provided by the driver in order to achieve overall directional control of the vehicle. Thus, in vehicle handling characteristics steering system plays very important role. The Pitman arm is a linkage attached to the steering box, sector shaft, that converts the angular motion of the sector shaft into the linear motion needed to steer the wheels. The Pitman arm is supported by the sector shaft on one side and on the other side to the drag link or center link with a ball joint. A performance study will be carried to analyze vibrational behavior and fatigue life of pitman arm using FEA tools. The structural optimization will be done on the pit man arm using Optistruct, changing the structure of pitman arm by removing the material from the surface where stress value is low. The meshing and boundary conditions will be applied using Hypermesh 12.0 and analysis will be carried out using ANSYS. The testing of Pitman arm is carried out for vibrational analysis and fatigue analysis and the result will be validated with the experimental results.**

***Index Terms* — Finite element analysis, Fatigue analysis, Modal analysis, Pitman arm, Topology optimization.**

I. INTRODUCTION

The Pitman arm is a steering component that is used in an automobile or truck. It is a linkage between sector shaft of the steering box and drag link. It transmits the angular motion to the linear motion that is required to steer the wheels in desired direction. The arm is attached to the sector shaft and supports the drag link or center link with a ball joint. It transmits the motion it receives from the steering box into the drag (or center) link, causing it to move left or right to turn the wheels in the appropriate direction. The idler arm is attached between the opposite side of the center link from the Pitman arm and the vehicle's frame to hold the center or drag link at the proper height. A worn ball joint or a sudden failure of pitman arm can cause severe damage and may get worse over time.

II. OBJECTIVES

- Vibrational behavior of pitman arm using FEA tools under actual loading conditions.
- To analyze the fatigue life of the component.
- Structural optimization for better design and increased efficiency.
- Fabrication and experimental validation of optimized model.

III. METHODOLGY

Phase I- Literature Survey

Phase II- Measurement and Design
Phase III- FEA and Analysis
Phase IV- Results and Conclusions
Phase V- Manufacturing and Testing
Phase VI- Validation and Report

IV. LITERATURE SURVEY

Sijith PM et al. [1] Performance study is carried out followed by static structural analysis and optimization to minimize the weight of the pitman arm and thereby reducing the material cost. Optimized model is then verified by physical testing. **Vimal Rau Aparow et al. [2]** has investigated 2 DOF mathematical models of Pitman arm steering system and derived using Newton's law of motion and modeled in MATLAB/SIMULINK software. The developed steering model is included with a DC motor model which is directly attached to the steering column. The performance of the electronically actuated Pitman arm steering system can be used to develop a firing-on-the-move actuator (FOMA) for an armored vehicle.

Srilekha Aurulla, G. and Gopala Krishna [3] has presented the static and modal analysis of steering lever link of a tractor to check its deformation, maximum stress and natural frequencies by using three materials.

Kazem Reza Kashyzadeh et al. [4] has studied and predicted fatigue life of suspension component and package of automotive suspension are the main purposes. First, using MATLAB software, road roughness according to the intercity roads for constant vehicle velocity (100Km/h) has been studied. After that frequency response of components has been analyzed, its critical points determined to calculate the fatigue life of the part, and the amount of critical stress obtained based on Von Misses, Tresca and Max Principle criterion for a quarter car model (passive suspension System in 206 Peugeot).

Aniket Kolekar et al. [5] has designed and fabricated the fixture which is used in the manufacturing of Pitman Arm of steering system. The fixture is designed by using software CATIAV5R21.The purpose of the fixture is to provide strength, holding, accuracy and interchangeability in the

manufacturing of product. The main purpose of a fixture is to locate and in the cases hold a work piece during an operation.

Yuvraj N. Doke and Sameer M. Shaikh [6] have investigated calculation of buckling strength for drag link. Also analysis of drag link tubes against compressive loads shown. Relations of various design parameters with buckling strength are shown.

P.D.Darade and Bimlesh Kumar [7] has embraced designing a mathematical model for foresee settling time, holding input parameters such as piezolocation, displacement and velocity. The significant intention of this research papers is to reduce time consumption and cost consume conserve in experimentation process. Here, Genetic algorithm (GA), cuckoo search (CS) and artificial bee colony (ABC) are the optimization techniques involve in this designing process to frame the mathematical model. Among, involved optimization techniques artificial bee colony behaves literally in minimizing error; this model will reveal settling time value as that of measured value in experimentation process by feeding input parameters such as piezolocation, displacement and velocity.

P.D.Darade and Bimlesh Kumar [8] has investigated optimal input parameters such as piezolocation, displacement and velocity to retrieve minimized settling time. His previous research work comprised of framing mathematical modelling, that model is utilized as an objective function to get the solution of minimized settling time. This previous developed mathematical model is subjected with three different optimization techniques such as cuckoo search (CS), artificial bee colony (ABC) and particle swarm optimization algorithms (PSO). Among, all three applied optimization techniques the proposed particle swarm optimization technique reveals better result (i.e.) achieving minimized settling time with optimal input parameters.

V. ANALYSIS OF PITMAN ARM

Fig.1 Real time pitman arm

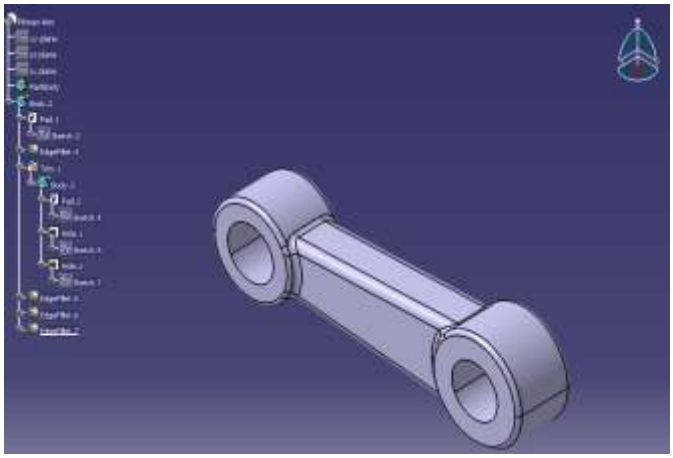


Fig.2 CAD model of pitman arm

Finite element analysis is a computational technique that is used in engineering to obtain approximate solutions of boundary value problems.

The following are the steps for pre and post processing in FEM. [1]

1. Define the geometry of the problem.
2. Discretize the model by meshing.
3. Define the element type(s) to be used.
4. Define the material properties of the elements.
5. Define the element connectivity.
6. Define the physical constraints (boundary conditions).
7. Define the loadings.
8. Solve the analytical problem.
9. Result evaluation.

Table 1 Material properties of Alloy Steel

Property	Value
Young's modulus (E)	2.1×10^{11} Mpa
Poisson's ratio (v)	0.3
Density (ρ)	7.9×10^{-6} kg/mm^3
Yield strength	520 Mpa

VI. FORCE CALCULATIONS

Total Mass of the vehicle, M_1= Curb weight + Passengers weight + Luggage

M_1= 1624 + 476 + 100 = 2200kg

This weight must be divided into front axle weight and rear axle weight. 52% of the total weight is taken by front axle and 48% is by rare axle.

Therefore, Mass on the front axle, M_2 = 1144kg

Mass on one of the front wheel, M = 572kg

Width of tire, B = 215mm

Center of rotation (king pin) to wheel, E = 120mm

Coefficient of friction, μ = 0.7

Distance from king pin center to tie rod center, L_1 = 145mm.

$$T = M \times g \times \mu \times \sqrt{\left(\frac{B^2}{8}\right) + E^2}$$

T=Torque required to rotate one wheel (torque at king pin),

T= 557967.351 N

$$F = \frac{T}{L1} = 3848.05 \text{ N}$$

Since single steering arm will be handling two wheels so the force on steering arm will be doubled.

F = 7696.1 N

Stress calculation:

$$\sigma = \frac{My}{I}$$

$\sigma =$ Maximum bending stress

$M =$ Bending moment

$y =$ Vertical distance away from the neutral axis

$I =$ Moment of inertia

$$y = \frac{b}{2}$$

$$= \frac{38.35}{2} = 19.175 \text{ mm.}$$

$$I = \frac{w \times b^3}{12}$$

$$= \frac{38.35 \times 30^3}{12} = 86287.5 \text{ mm}^4.$$

$$M = F \times L$$

$$= 7696.1 \times 127.5 = 981252.75 \text{ N} - \text{mm}.$$

The maximum bending stress

$$\sigma = \frac{My}{I}$$

$$= \frac{981252.75 \times 19.175}{86287.5}$$

$$= 170.5 \text{ Mpa.}$$

Vibration analysis (frequency calculation):

For natural frequency,

$$\omega_n = k^2 \times \sqrt{\frac{EI}{A\rho L^4}} \times \frac{1}{2\pi}$$

Where, $k = (2n-1) \times \frac{\pi}{2}$

1st mode frequency

$$\omega_1 = 1.571^2 \times \sqrt{\frac{2.1 \times 10^{11} \times 8.62 \times 10^{-8}}{3.60 \times 10^{-2} \times 7900 \times 0.127^4}} \times \frac{1}{2\pi}$$

$$= 1275 \text{ Hz}$$

2nd mode frequency

$$\omega_2 = 4.713^2 \times \sqrt{\frac{2.1 \times 10^{11} \times 8.62 \times 10^{-8}}{3.60 \times 10^{-2} \times 7900 \times 0.127^4}} \times \frac{1}{2\pi}$$

$$= 1722 \text{ Hz}$$

3rd mode frequency

$$\omega_3 = 7.855^2 \times \sqrt{\frac{2.1 \times 10^{11} \times 8.62 \times 10^{-8}}{3.60 \times 10^{-2} \times 7900 \times 0.127^4}} \times \frac{1}{2\pi}$$

$$= 4822 \text{ Hz}$$

Fatigue life calculation:

$$N = 10^{-c/b} \times {S_a}^{1/b}$$

$$b = \frac{-1}{3} \times \log \frac{0.8 S_{ut}}{S_e}$$

$$c = \log \frac{(0.8 S_{ut})^2}{S_e}$$

N = Number of life cycles before failure

S_{ut} = Ultimate tensile strength

S_a = Stress amplitude

S_e = Endurance

$$S_{ut} = 520Mpa = 53.025kg/mm^3$$

$$S_a = 0.8S_{ut} = 0.8 \times 53.025 = 42.42 kg/mm^3$$

$$S_e = 0.5S_{ut} = 0.5 \times 53.025 = 26.51 kg/mm^3$$

$$b = \frac{-1}{3} \times \log\frac{42.42}{26.51} = -0.1567$$

$$c = \log\frac{42.42^2}{26.51} = 4.21$$

$$N = 10^{-4.21/-0.1567} \times 42.42^{1/-0.1567}$$

$$= 3.09 \times 10^{16}$$

The existing pitman arm will fail after 3.09 x 10^{16} cycles. We say that component is having infinite life if it exceeds one lakh cycles.

VII. FINITE ELEMENT ANALYSIS OF PITMAN ARM

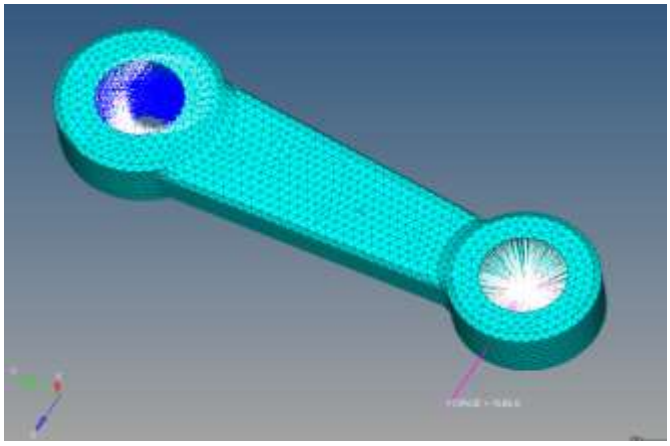


Fig.3 Meshed model with boundary conditions

For analysis, one end of the pitman arm (larger side connected to sector shaft) is rigidly fixed and on other end load is applied i.e. of 7696.1 N

Deformation plot

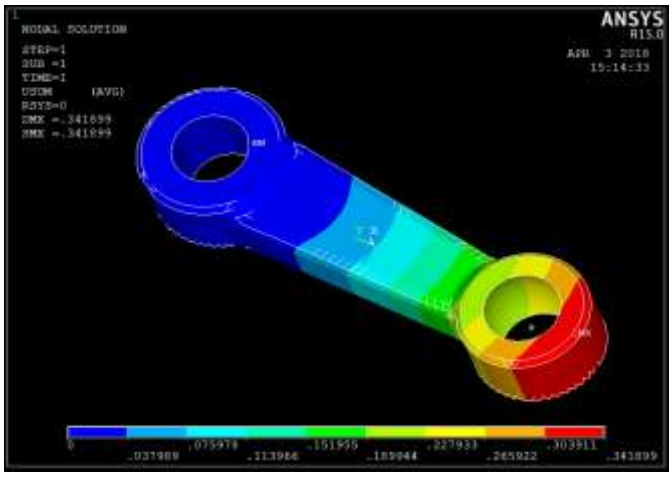


Fig.4 Displacement result for pitman arm

Maximum deformation is **0.30 mm**

Stress plot

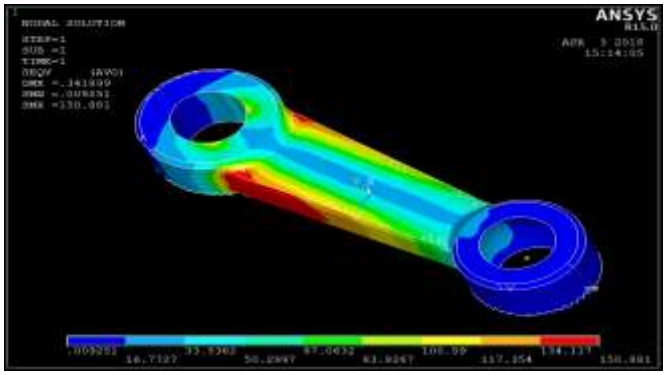


Fig.5 von-mises stress for pitman arm

Maximum Stress obsreved is **132.94 Mpa.**

As stress is well within the limit and deformation is less hence there is scope for optimization.

VIII. VIBRATIONAL ANALYSIS AND FATIGUE ANALYSIS

Results for modal analysis:

Mode 1:

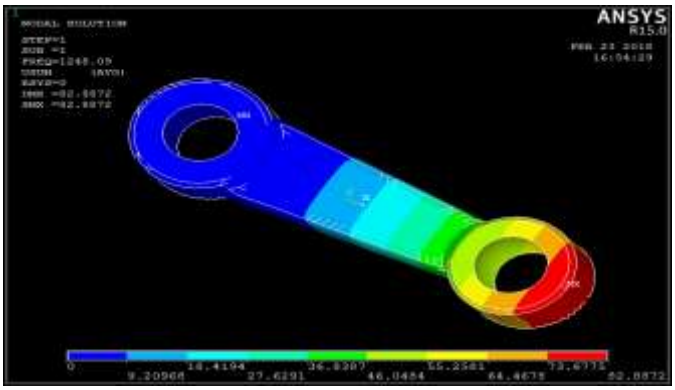


Fig.6: 1st mode frequency of pitman arm

The frequency of 1st mode is **1248.09** Hz.

Mode 2:

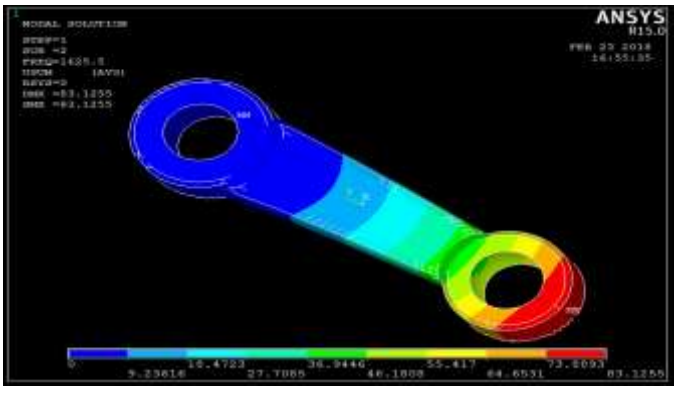


Fig.7: 2nd mode frequency of pitman arm

The frequency of 2nd mode is **1625.5** Hz.

Mode 3:

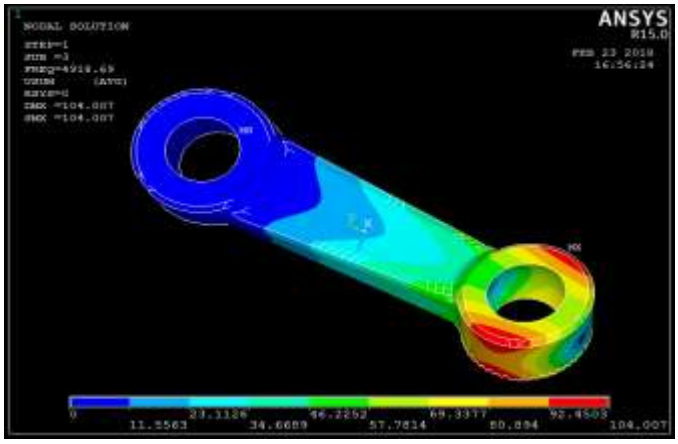


Fig.8: 3rd mode frequency of pitman arm

The frequency of 3rd mode is **4918.69** Hz.

Mode 4:

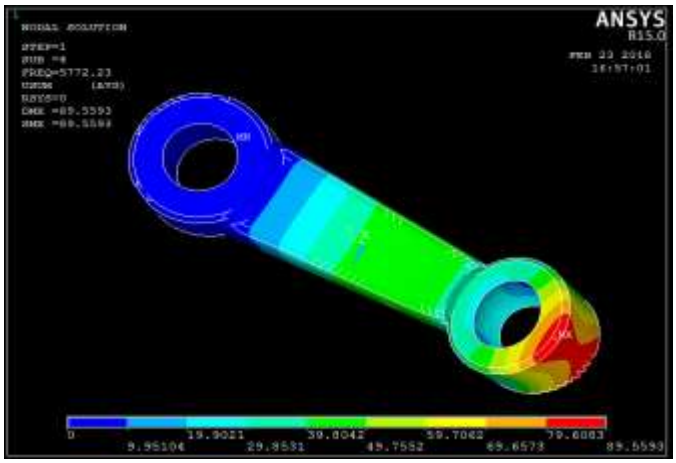


Fig.9: 4th mode frequency of pitman arm

The frequency of 4th mode is **5772.23** Hz.

Mode 5:

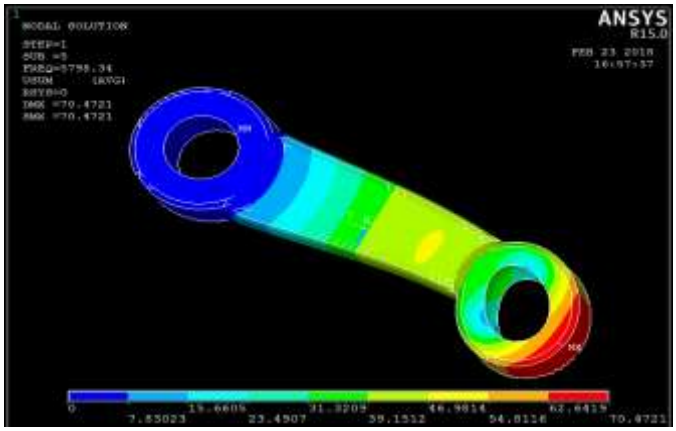


Fig.10: 5th mode frequency of pitman arm

The frequency of 5th mode is **5798.34** Hz**.**

Mode 6:

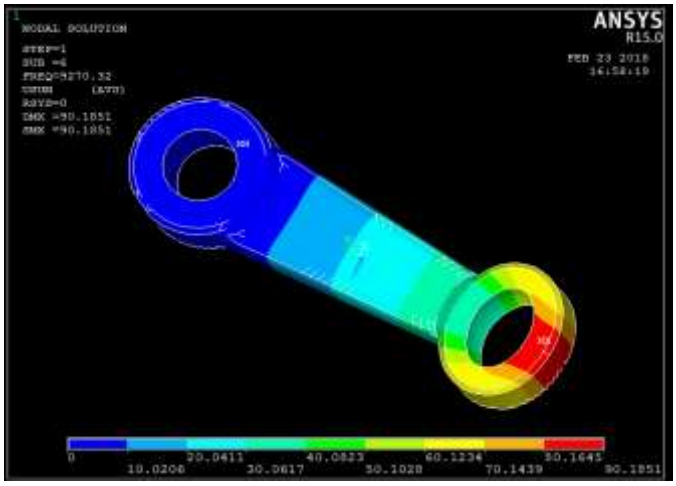


Fig.11: 6th mode frequency of pitman arm

The frequency of 6th mode is **9270.32** Hz.

After this we have done fatigue analysis of existing pitman arm.

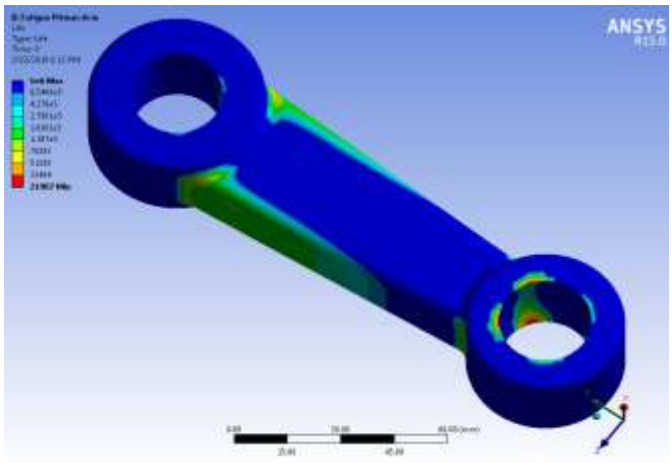


Fig.12 Fatigue life of specimen

Life of specimen – 10, 00,000 cycles

IX. TOPOLOGY OPTIMIZATION METHODOLOGY

It uses highly advanced optimization algorithms; OptiStruct can solve the most complex optimization problems with thousands of design variables in a short period of time. OptiStruct advanced optimization engine allows users to combine topology, topography, size and shape optimization methods to create better and more alternative design proposals leading to structurally sound and lightweight design. Manufacturing requirements can also be defined as input to the simulation to create design proposals that are easier to interpret and to manufacture.

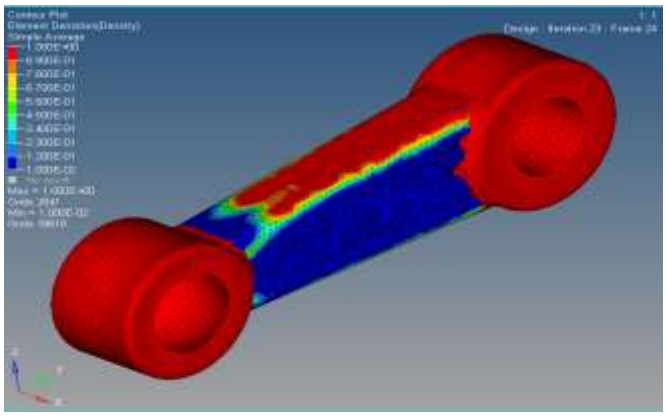


Fig.13 Topology optimization using Optistruct

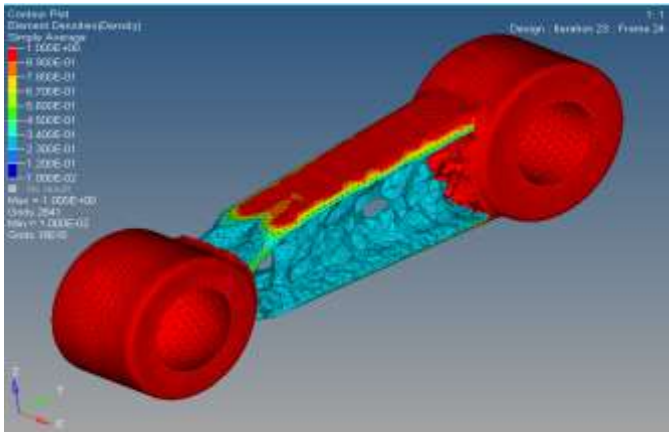


Fig.14 25% of material is removed from stress free region.

From topology optimization we can see that there is scope for material removal and we create a 6 mm depth slot on both sides of the pitman arm.

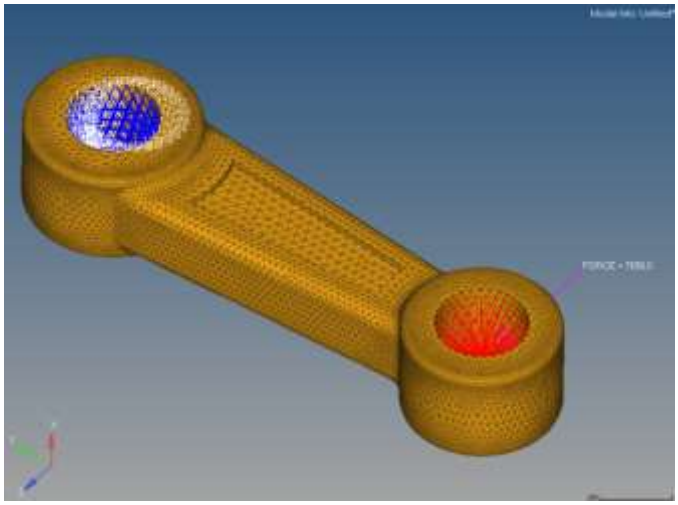


Fig.15 Optimized pitman arm with applied boundary conditions in Hypermesh.

X. RESULTS FOR STRESS AND DEFLECTION OF PITMAN ARM WITH 6MM SLOTTING

Result for Deflection:

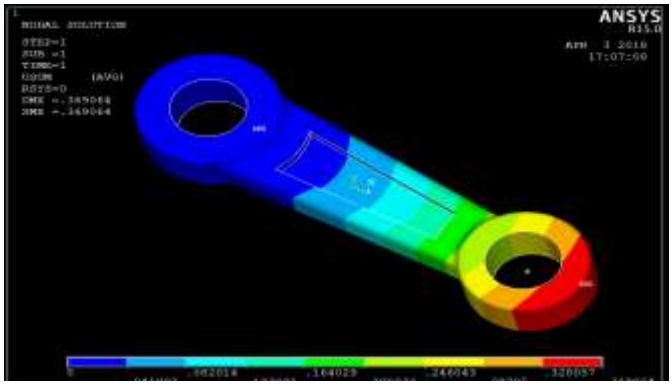


Fig.16 Displacement result for pitman arm

From Fig.16 it can be seen that the deformation is 0.369 mm

Result for Stress

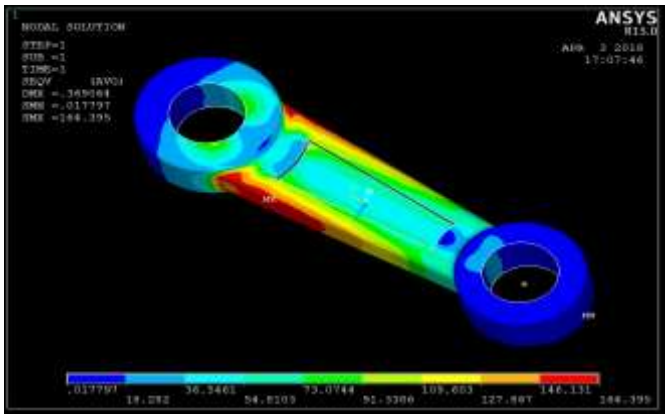


Fig.17 von-mises stress for pitman arm.

From fig.17 it can be seen that the maximum stress is164.39 MPa.

As the stress induced is **164.39** MPa, which is well below the critical limit. Hence, pitman arm with 6 mm slotting is considered in optimization.

Vibrational Analysis (Modal Analysis) And Fatigue Analysis

Mode 1:

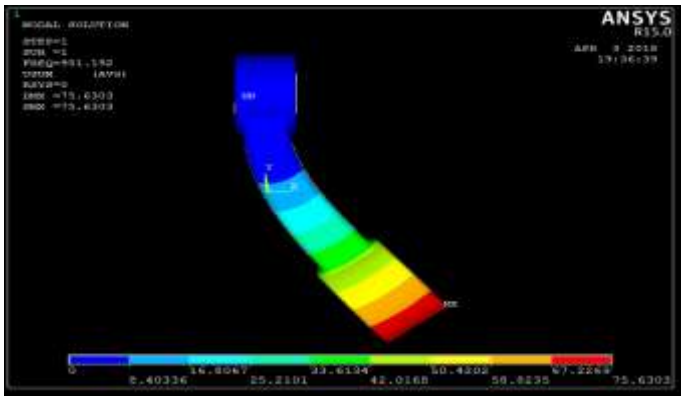


Fig.18: 1st mode frequency of optimized pitman arm

The frequency of 1st mode is **951.19** Hz.

Mode 2:

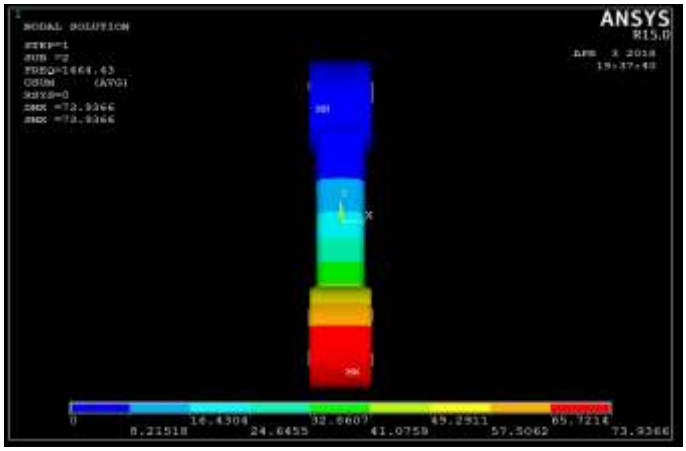


Fig.19: 2nd mode frequency of optimized pitman arm

The frequency of 2nd mode is **1464.43** Hz.

Mode 3:

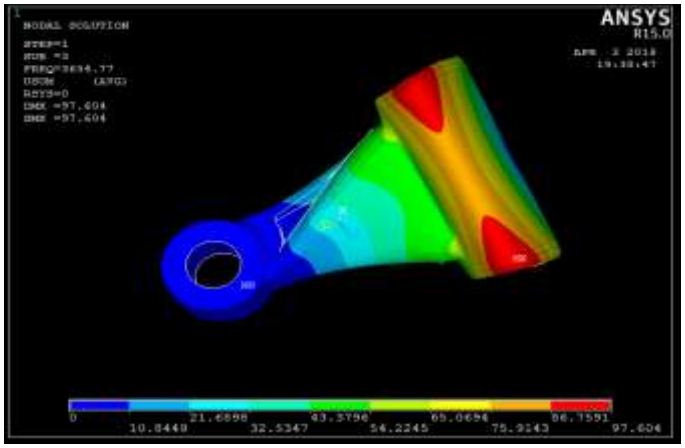


Fig.20: 3rd mode frequency of optimized pitman arm

The frequency of 3rd mode is **3654.77** Hz

Mode 4:

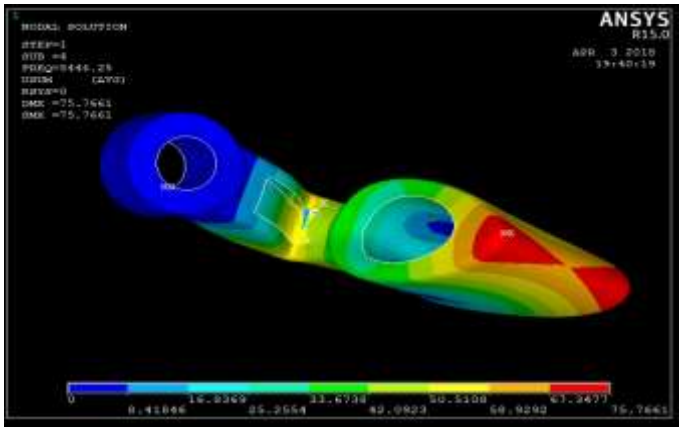


Fig.21: 4th mode frequency of optimized pitman arm

The frequency of 4th mode is **5446.25** Hz.

Mode 5:

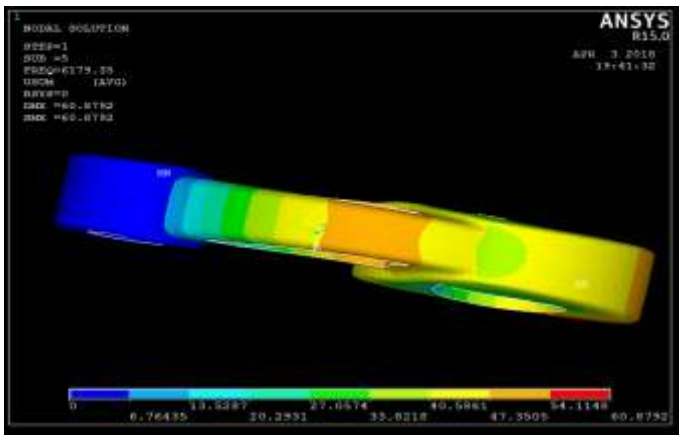


Fig.22: 5th mode frequency of optimized pitman arm

The frequency of 5th mode is **6179.35** Hz.

Mode 6:

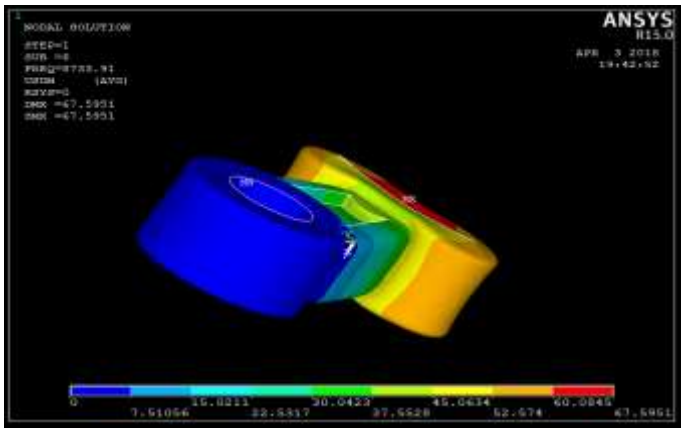


Fig.23: 6th mode frequency of optimized pitman arm

The frequency of 6th mode is **8733.91** Hz.

After this the fatigue analysis of this optimized pitman arm is carried out.

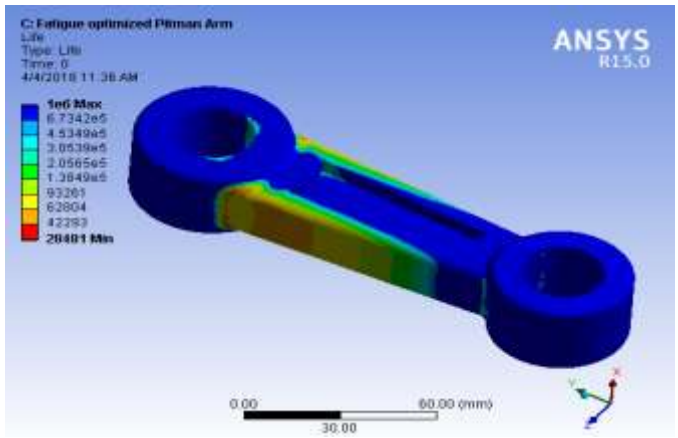


Fig.24 Fatigue life of specimen

Life of specimen – 10, 00,000 cycles

XI. RESULTS AND DISCUSSIONS

Table 2 Comparison of structural analysis results

Material Steel	Existing Model	Optimized 6 mm slot
Deformation (mm)	0.34 mm	0.369
Stress (Mpa)	150.88 Mpa	164.395 Mpa
Weight	1.073 Kg	0.976 Kg (9.04% weight reduction)

Table 3 Comparison of vibrational (modal) analysis results

Sr. No.	**Mode**	**Frequency (Hz)**	
		Existing	**Optimized 6 mm slot**
1	1	1248.08	951.19
2	2	1625.5	1464.43
3	3	4918.69	3654.77
4	4	5772.23	5446.25
5	5	5798.34	6179.35
6	6	9270.32	8733.91

Table 4 Comparison of Fatigue life

Fatigue Life	**Minimum (cycles)**	**Maximum (cycles)**
Existing steel Model	21907	1000000
Optimized 6 mm slot model	28481	1000000

XII. MANUFACTURING AND TESTING

Fabrication of optimized pitman arm

Fabrication of optimized pitman arm is done by considering thick steel plate of 30 mm thickness, later the plate is cut into required shape of pitman arm according to design drawing with the help of water jet cutting machine. Then milling is done to required depth according to optimized drawing in milling machine as shown in the figure below.

Fig.24 Rough cutting of 30 mm thickness plate as per required dimension using water jet machine

Fig.25 Final fabricated pitman arm according to optimized dimensions after milling operation.

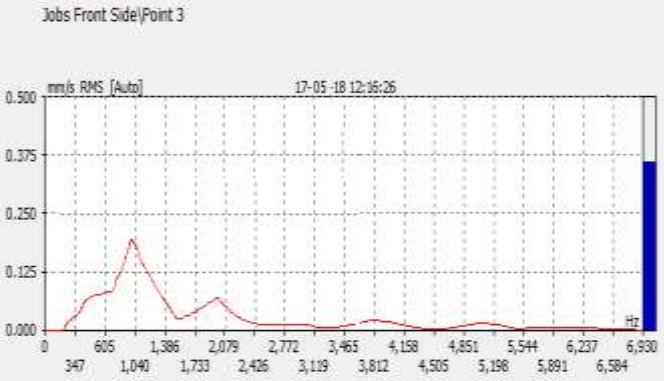
Experimental Testing of Pitman Arm

To validate the above modal analysis results, experimental testing has been done with the help of portable FFT analyzer to find out the frequencies for respective modes of vibration. Since the specification of the portable FFT analyzer is restricted. That is the accelerometer of FFT analyzer is capable of sensing only translation in any one of the direction. we can carry the test for only x y z translations and get the respective frequencies and amplitude once results for three translations gets matched with FEA results. It has been considered that the reaming three rotations will be in good arrangement with FEA results.

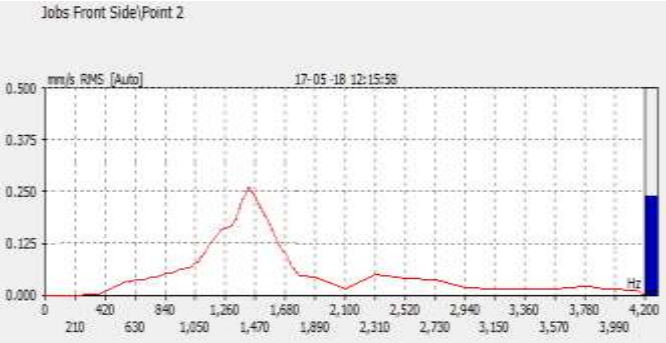
Fig.26 Boundary Conditions as considered in FEA.

Fig.27 FFT Analyzer with Uni-axial Accelerometer (transducer)

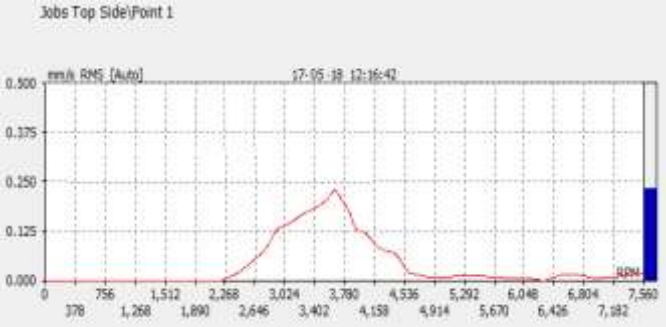
Test Plots



Frequency recorded at peak: 950 Hz



Frequency recorded at peak: 1450 Hz



Frequency recorded at peak: 3650 Hz

Table 5 Comparison of FEA and Experimental results

Modes	FEA Frequency (Hz)	FFT Experimental Frequency (Hz)	% Error
Mode 1	951.19	950	1.3
Mode 2	1464.43	1450	3.2
Mode 3	3654.77	3650	1.1

From the above comparison table we can observe that experimental results obtained by FFT analyzer for first three mode shapes are in good arrangement with respective FEA results.

As we observed here, the magnitude of frequencies are very high because the optimized pitman arm is completely fixed at the bottom so there are very less chances to vibrate during normal operating conditions to make it vibrate or the resonance to occur with the operating frequency of the vehicle. Vehicle has to vibrate with the high operating speed. So the optimized pitman arm will be safe under normal operating conditions.

Fatigue Testing:

Fig. 28 Fatigue test setup.

Table 6 Fatigue test results.

Sr. No.	Sample Name	Test Description	Test Conditions	Test Results
1	Optimized Pitman Arm	Fatigue test	Frequency: 28 Hz Load:7696N	100800 cycles

Even after completion of one lakh cycles, no any failure or initiations are observed in the optimized model so the model is considered to be safe and optimized successfully.

XIII. CONCLUSION

- Static and modal analysis results of existing pitman arm proved that the model is more stable and there is scope for optimization.
- The comparison, between modal analysis results of existing and optimized pitman arm has been performed and it is observed that the pitman arm is vibrationally stable.
- The comparison, between fatigue life results of existing and optimized pitman arm has been performed and it is observed that the pitman arm is having infinite life.
- Optimization of pitman arm is done successfully using OptiStruct software and weight of the component is reduced successfully upto 10%.
- Modal and fatigue results are validated experimentally by performing vibration and fatigue testing of the optimized pitman arm on FFT Analyzer and fatigue testing machine.

The above steady confirmed the optimized pitman arm is Vibrational, structurally stable with good fatigue life.

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