Topology Optimization of Front Leaf Spring Mounting Bracket

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***Abstract*—Automotive industry is the largest growing & widely spread industry today. And the industry is continuing to strive for light weight vehicle in improving fuel efficiency and emission reduction performance. To optimize cost and weight parameters, a correct approach of cost management in the product development process is necessary. This paper outlines the various methods of topology optimization and reviewing the tool of topology optimization for the design & development of various automotive components. Using various techniques of shape, size & topology optimization may subsystems of automobile can be designed for light weighting without compromising strength of the components with increase in component compatibility. Paper also overviews various areas in which topology optimization is used successfully to achieve significant weight loss and ultimately increasing performance of automobile with considerable reduction in cost. Topology optimization of Leaf Spring Mounting Bracket is performed here as a case study and which results in 19.39 % of weight reduction without compromising strength of the bracket. Topology is scientific tool that provides guideline about removing of inefficient material from the structure**

***Index Terms*—Ansys 16.0 & 18.0, BESO, Evolutionary Structural Optimization (ESO), Shape Optimization, Size Optimization, Topology Optimization (TO)**

I. INTRODUCTION

In the present tough international competition, automotive companies can only survive if they can provide cost optimized, light-weighted, resource-efficient, and durable and stable products. At the same time, the product must be introduced quickly into the market. These demands can only be met if

structural optimization tools are used in addition to established CAE, CAD, DMU and PDM systems.

In this paper a suspension bracket (leaf spring mounting bracket) of Mahindra Classic Jeep has been analyzed and topologically optimized to reduce its weight but without compromising its strength. Modal analysis is also carried out and it shows that the minimum natural frequency is much above the road excitation frequency range. That means condition of resonance will be avoided and so as the maximum stress value will exceed the safe value anyway. All the analysis and optimization is done in Ansys 19.0 as now Ansys has introduced topology optimization option in version 18.0 and above. Evolutionary Structural Optimization Method (ESO) is used here for optimization.

Structure topology optimization design is a complex multi-standard, multi-disciplinary optimization theory, which can be divided into three category Sizing optimization, Shape optimization and material selection, Topology optimization according to the structural optimization model or optimize layers. Topology optimization is usually also known as the optimization of the distribution (or layout optimization, shape optimization of a broad sense), and its importance is to find the best possible topology or layout in given design objectives and constraints, usually has the most decisive factor in the efficiency of the development of new products.

The light weighting of vehicle is important objective of such topology optimization. There are three common approaches to minimize vehicle weight in practice that are; substitution with light weight material, downsizing of vehicle and removing unwanted material from the structural component. Solutions obtained by standard size and shape optimization methods keep the same topology of the initial design. These solutions are often far from optimal because other competing topologies cannot be explored. For this reason, topology optimization methods are becoming increasingly important as potential tools in engineering design.

➢ THEORY

Generally, vehicle product development process can be divided into four stages: 1) Conceptual design stage; 2) Detailed design stage; 3) Product shaping stage; 4) Structure improving design after batch production. Domestic and foreign scholars have conducted extensive researches and application exploration, finally worked out the two key factors that impact of CAE about car body in concept development: the rapid construction of the analysis model requirements for different design plan and size modification; rapid achievement of various plans comparing in performance and structural design optimization. (This aspect has been mature relatively in technology due to the progress of structural analysis method and the application of powerful analysis software). The fundamental differences between topology optimization and the traditional design, CAE analysis design: Topology optimization separated the trial production from structure analysis, avoided actual sample car production before the stereotypes of basic products, accordingly achieve both cost saving and improvement of efficiency. Here the basics of optimization in general and topology optimization in particular will be described.

- **Mathematical optimization**

The basic principle of optimization is to find the best possible solution under given circumstances. One example of optimization is finding the quickest route when using the public transportation system or, as in the case of structural optimization, finding the optimal distribution of material that satisfies some given requirements. This is most often done by decisions made by the passenger or the engineer from their own experience and knowledge about the subject. The objective of the optimization problem is often some sort of maximization or minimization, for example minimization of required time or maximization of stiffness. To be able to find the optimum solution the `goodness' of a solution depending on a particular set of design variables needs to be expressed with a numerical value. This is typically done with a function of the design variables known as the cost function. Mathematically the general optimization problem is most often formulated as minimization of the cost function (which can easily be transformed to maximization by minimizing the negative function) subject to constraints, this can be expressed as:

$$\text{Find } \boldsymbol{x} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \text{ which minimizes } f(\boldsymbol{x})$$

$$\text{subject to } \begin{cases} g_i(\boldsymbol{x}) \leq 0, \ i = 1, 2, \ldots, m \\ h_j(\boldsymbol{x}) = 0, \ j = 1, 2, \ldots, n \end{cases}$$

Where x is the vector of design parameters and f(x) is the cost function. The functions gi(x) and hj(x) are called the inequality constraint function and the equality constraint function respectively and they define the constraints of the problem. This is called a constrained optimization problem.

- **Structural optimization**

Structural optimization is one application of optimization. Here the purpose is to find the optimal material distribution according to some given demands of a structure. Some common functions to minimize are the mass, displacement or the compliance (strain energy). This problem is most often subject to some constraints, for example constraints on the mass or on the size of the component. This optimization is traditionally done manually using an iterative-intuitive process that roughly consists of the following steps:

1. A design is suggested
2. The requirements of the design is evaluated, for example by a finite element analysis (FEA)
3. If the requirements are fulfilled, the optimization process is finished. Else, modifications are made, a new improved design is proposed and step 2-3 are repeated.

The result depends heavily on the designer's knowledge, experience and intuitive understanding of the problem. Changes to the design are made in an intuitive way, often using trial and error. This process can be very time consuming and may result in a suboptimal design.

The problem of structural optimization can, according to Christensen and Klarbring, be separated in three different areas: sizing optimization, shape optimization and topology optimization see Figure 1.

- **Sizing optimization**

Sizing optimization is the simplest form of structural optimization. The shape of the structure is known, and the objective is to optimize the structure by adjusting sizes of the components. Here the design variables are the sizes of the structural elements, for example the diameter of a rod or the thickness of a beam or a sheet metal. See Figure (1.a) for an example of size optimization where the diameter of the rods is the design variables.

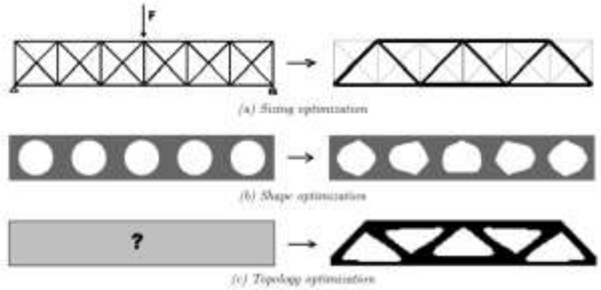

Fig. 1: Different types of structural optimization

- **Shape optimization**

As with sizing optimization the topology (number of holes, beams, etc.) of the structure is already known when using shape optimization, the shape optimization will not result in new holes or split bodies apart. In shape optimization the design variables can for example be thickness distribution along structural members, diameter of holes, radii of fillets or any other measure. See Figure (1-b) for an example of shape optimization. A fundamental difference between shape vs. topology and size optimization is that instead of having one or more design variable for each element the design variables in shape optimization each affect many elements.

II. Literature Survey:

Many research scholars have studied and proposed various methods of Topology Optimization for optimizing different structural components of automobile since longer time. They have found topology as very effective and powerful tool for structural optimization. The primary purpose of many experiments is found to be weight reduction.

Mayur Jagatap and Ashvin Dhoke, two CAE engineers from TechMahindra have used Altair Optistruct as tool for design and optimize cast iron Exhaust mounting bracket. Topologically Optimized design was finalized based on manufacturing feasibility and other practical constraint. They have achieved 45% mass reduction and 50% of design cycle time and without compromising in strength and fatigue life criteria. In future they are going to consider shape optimization for design. [1]

Y. S. Kong, S. Abdullah, M. Z. Omar and S. M. Harisin their paper published in LAJSS (2016), have optimized Automotive Spring Lower Seat using topological and topographical techniques. In their work 36.5% mass reduction and 27% compliance increase was achieved. [2]

Subhash Sudalaimuthu, Barry Lin, Mohd. Sithik and Rajiv Rajendramin their SAE International Paper (2016) have explained process of designing lightweight track bar bracket right from the scratch. Design of Experiments (DOE) and topology optimization is used to decide bolt locations and critical load path and followed shape optimization to finalize the shape. [3]

Suresh Kumar Kandreegula, Naveen Sukumar, Sunil Endugu and Umashanker Gupta published a SAE International paper in 2015 in which they have provided a forum to present new developments in structural Non-linear topology optimization. By this method structural optimization on irregular design domains can be carried out easily. Transmission Housing has been optimized using Non-linear Topology Optimization technique with the help of Simulation tool Altair OptiStruct& verified experimentally. They achieved cost reduction without sacrificing performance & safety. [4]

Guan Zhou, Guangyao Li, Aiguo Cheng, and Guochun Wang,Hongmin Zhang and Yi Liao (2015 SAE Paper) have done topology optimization on Auto Body for light weighting. They found weak part in BIW (Body in White) by applying Topology optimization and then performed sensitivity analysis to optimize thickness and significant weight reduction was achieved. Density method of Topology Optimization is used in this for Optimization. [5]

In another SAEresearch article (2015), **Bo Tan, Yu Yang, Jun Huang, Wenhui Liu, and Dongqing Zhanghave** have done structural optimization of Heavy Truck Propeller Shaft Bracket. Effect of bracket structure mode on the frequency response and stress on it are studied. In this they combine finite element method and the multi-body dynamics technology to present NVH vibration improvement of heavy truck drive shaft system. Topology optimization technology provides support to the structure improvement. [6]

Guangiyo Li, Xiaudong Xu and colleagues have topologically optimized an Automotive Tailor-Welded Blank(TWB) Door, tells their ASME paper in 2015. Bidirectional Evolutionary Optimization Method (BESO) is extended here to optimize TWB

Door with multiple thicknesses then proposed optimization method for TWBs. This method can provide guide for light weight design for other automotive TWB components. [7]

BGN Satya Prasad and M Anil Kumar managers from Hyundai Motor India Engineering presented a paper in Altair Technology Conference 2013 India regarding Topology Optimization of Alloy Wheel. They used the technique of topology to design a lightweight Aluminum wheel using Hypermesh and Optistruct. Mass reduction of 340 gm per wheel is achieved by them. [8]

Parag Nemichand Jain and Satish Pavuluri from Ashok Leyland, Ltd. in 2013 published their work in SAE journal about Experimental and Finite Elemental Analysis of Bogie Suspension Mounting Brackets. This analysis helped to create a methodology to analyze bogie suspension brackets. [9]

Brake Actuator Mounting Bracket was optimized in 2010 by **Vasudev Rao S. and Chetan Raval** from Mahindra Engineering Services. This shows their work in HTC. Altair HyperWorksOptistruct was their optimization tool. Objective was to minimize total static deflection of bracket. They achieved it within reduced time. [10]

Some literatures have reviewed various applications of topology optimization in automotive applications [11] as well as use topology, shape & size optimization at various stages of design is also described [14].

Tool of topology optimization is mainly used for mass reduction in many structural applications like Engine Mounting Bracket, Transmission Housing Bracket, Cabin Suspension Bracket, Air filter bracket, Steering Column Bracket, tooled transmission mount, and jounce bump bracket. [13], [15], [16].

Topology Optimization is becoming more important in structural design which also can solve multiple loading condition problems. Basic formulation of TO problem can be found in SAE paper.

Main Key Highlights from the literature survey are as follows:

- Main purpose of most of the researchers was the weight reduction in individual component.
- Along with weight reduction compliance minimization (i.e. stiffness increase) and natural frequency maximization was also the important considerations.
- Shape, Size and topology optimizations are used in combinations by many researchers to get most optimized structure.
- Density method and ESO methods are more often used for the optimization.
- Altair Optistruct as most powerful Software package is used.
- Presently Ansys 18.0 and above versions are containing Topology Optimization Module separately which is used in this present work.

III. TOPOLOGY OPTIMIZATION OF BRACKET:

- **Flow of Topology Optimization:**

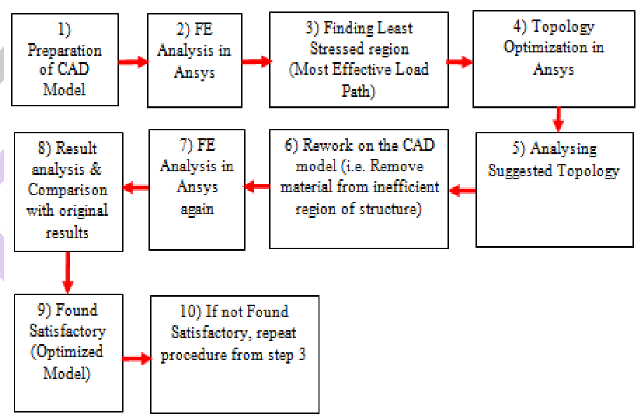

Fig. 3: Flow of Topology Optimization

- **CAD Model Preparation:**

3-D CAD Model is prepared in CATIA V5 part modeling. Leaf spring is attached to two brackets one at front end and other at rear end. Both brackets modelled in the software as shown below.

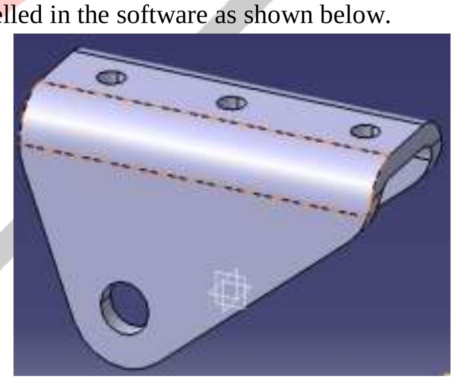

Fig. 4: Front End Bracket

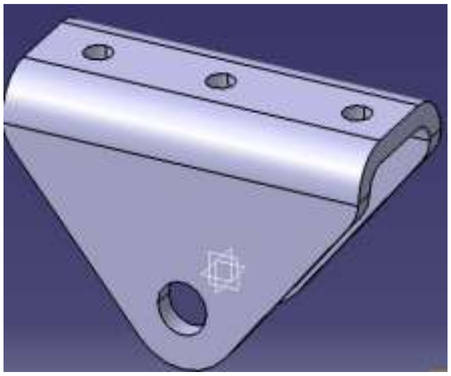

Fig. 5: Rear End Bracket

- **Finite Element Analysis (Original Model): Static Structural**

FE Analysis is carried out in **Ansys R19.0 Academic.** It has special module for Topology Optimization. Only **Front-End Bracket** is optimized here. It is carried out in following steps.

A. Meshing:

Ansys default meshing is used to mesh the model. No any special mesh refining or special element type is used for meshing. Mesh statistics shows **11723 number of nodes and 6285 number of elements**.

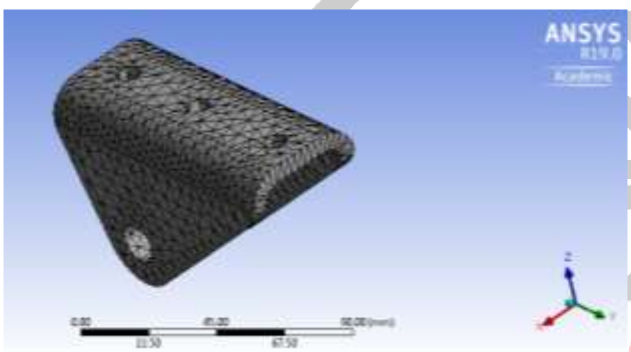

Fig. 6: Mesh Model

B. Boundary Conditions:

- **Supports & Displacement**

In this surface of mounting hole is fixed and the translation of upper surface made zero in the direction perpendicular to its surface (i.e. Z direction) and made free in other two directions.

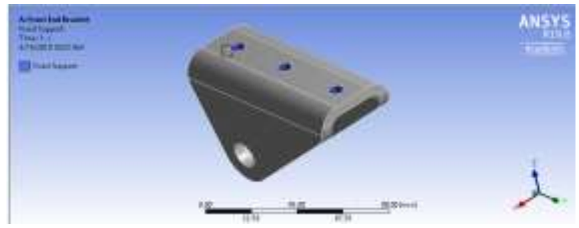

Fig. 7: Fixed Support

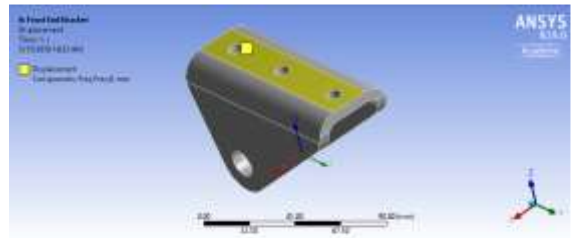

Fig. 8: Displacement

- **Loading and Material:**
  - ***Material:*** Material assigned for bracket is Structural Steel which has following properties;
    Yield Strength Syt = **250 MPa**
    Ultimate Tensile Strength = **460 MPa**
    Young's Modulus, E =**210 GPa**
    Poisson's ratio, ν = **0.3**

  - ***Load Calculations:***

Gross Vehicle Weight is 1600 kg. And with occupant & other material we can consider 500 kg extra. Therefore, total vehicle weight is 1600+500=**2100** kg
Force Coming on 1 wheel=2100/4=525 kg=525x9.81=**5150.25 N (5200 N Approx.)**
This force will be transferred from suspension. Front suspension is leaf spring type and has two brackets of two ends. We will consider Front End Bracket for static topology optimization and modal optimization for weight reduction.

  - ***Loading in Ansys:***

Load of 5200 N is given at the two holes in which bolt of the leaf spring eye is supported as shown in figure 9 below.

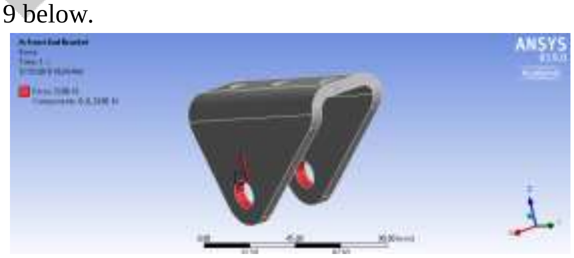

Fig. 9: Loading

C. **Results:**

Total deformation, Equivalent stress and Safety factor is found out in the bracket.

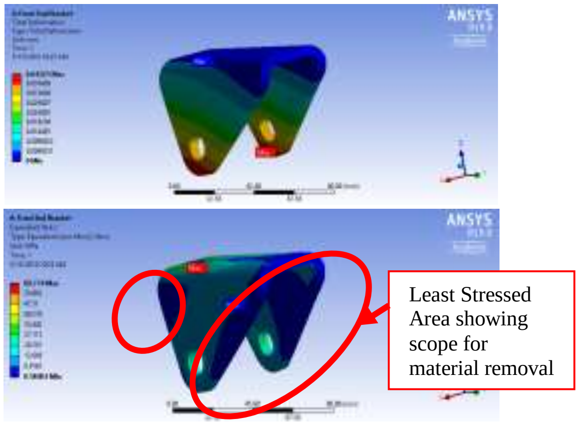

Fig. 10: Total Deformation, Equivalent Stress

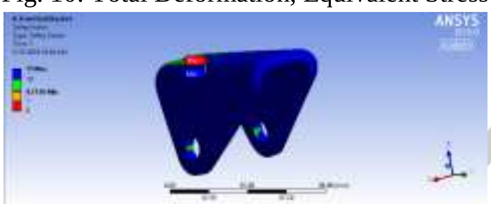

Fig. 11: Safety Factor

Table No. 1: Static Structural Results of Original Bracket

Sr. No.	Parameter	Value
1	Total Deformation	0.043 mm
2	Equivalent Stress	**60.774 MPa**
3	Safety Factor Minimum	**4.1136**
4	Weight of the Bracket	**0.526 kg**

Factor of Safety is **4.1136** which is almost over safe for static loading. Hence there is scope for optimization. Figure of Stress is showing the least stressed area which is we can scope for material removal.

D. Modal Analysis:

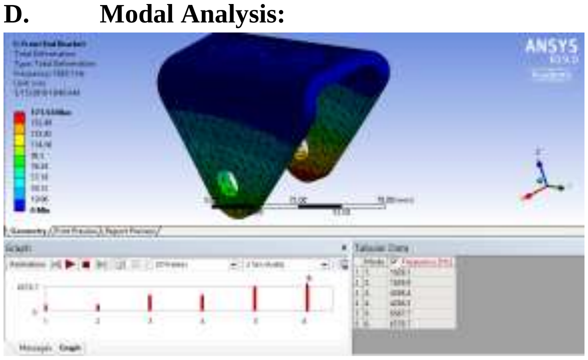

Fig. 12: Modal Analysis of Original Bracket

Figure shows that minimum natural frequency of original bracket is **1628.1 Hz** which too far from road excitation natural frequency ranging from **0 to 20 Hz**. Hence bracket is safe in dynamic loading also.

➢ **Topology Optimization in Ansys:**

Figure 11 below is showing the **design and non-design** area in Ansys. We can make any changes in design area only. Non-design area is generally area with boundary condition. Fig 12 is showing the suggested topology by the software when objective of compliance minimization and mass reduction of 30% was given to it. We can see the area with removed material. Suggested Optimization reduces mass of bracket from **0.525 kg to 0.384 kg which around 27% reduced**.

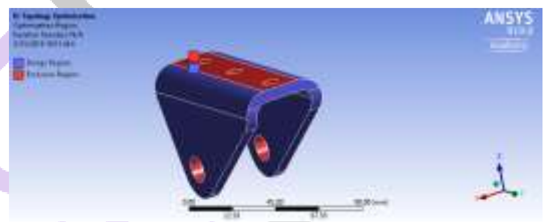

Fig. 13: Design and Non-Design Area

Fig. 14: Suggested topology

IV. BRACKET MODIFICATION AND RE-ANALYSIS:

A. Following figure shows the modified form of the bracket.

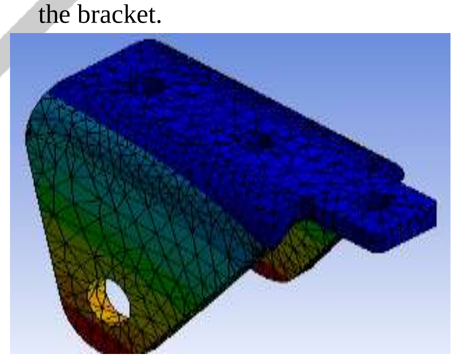

Fig. 15: Modified Bracket

B. Analysis of Modified Bracket:

All the mesh properties and boundary conditions kept unchanged and results simulated again. Following figures shows the analysis results.

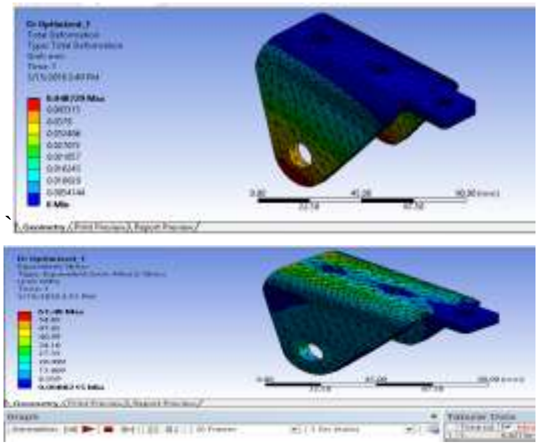

Fig. 16: Total Deformation, Equivalent Stress of modified bracket

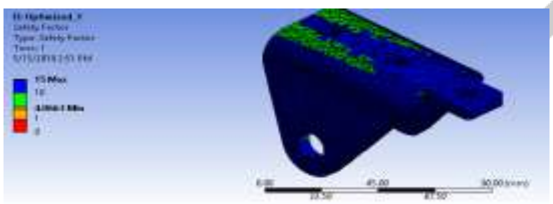

Fig. 17: Safety Factor of Modified Bracket

Table No. 2: Static Structural Results of Modified Bracket

Sr. No.	Parameter	Value
1	Total Deformation	0.048 mm
2	Equivalent Stress	**61.48 MPa**
3	Safety Factor Minimum	**4.066**
4	Weight of Bracket	**0.424 kg**

C. Modal Analysis of Modified Bracket

Modal analysis of Modified bracket shows minimum natural frequency of **1616.4 Hz** means almost no compromise with natural frequency. Means new bracket is also safe in dynamic loading.

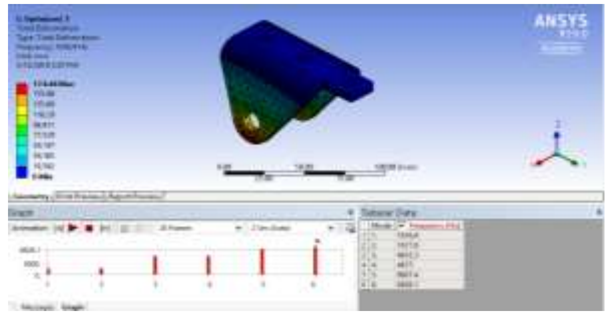

Fig. 18: Modal Analysis of Modified Bracket

V. RESULT COMPARISON:

Table No. 3: Result Comparison

Sr. No.	Parameter	Value for Original Bracket	Value for Modified Bracket	Difference (New-Original)
1	Total Deformation	0.043 mm	0.048 mm	0.005 mm
2	Equivalent Stress	**60.774 MPa**	**61.48 MPa**	**0.706 MPa**
3	Safety Factor Minimum	**4.1136**	**4.066**	**-0.047**
4	Weight of Bracket	**0.526 kg**	**0.424 kg**	**-0.102 kg (19.39 %)**

VI. CONCLUSION

From the comparison of the result it is concluded that topology optimization is very effective tool for optimization. In this case weight reduction of **19.39 %** is observed almost without compromising strength and factor of safety.

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