Mass Optimization of Automotive Radial Arm Using FEA for Modal and Static structural Analysis

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Abstract. The radial arm is an important part of an automobile suspension system. A vehicle suspension system having radial arms that are connected to axle brackets through vertically arranged bushings. The radial arms are fabricated using sheet metal members that are assembled in a clam-shell arrangement. An important consideration in the design of radial arm is the natural frequencies and mode shapes for dynamic loading conditions along with stiffness. The present work is focused on mass optimization of radial arm for modal and static structural analysis. The work includes investigation of natural frequencies and mode shapes of the optimized design of radial arm and comparing with the static structural analysis results using Finite element analysis tool. The radial arm was modeled in Catia V5, finite element modeling was done in Altair Hypermesh and analysis was done using Optistruct solver. From the static stiffness analysis, it was observed that the mass of the assembly can be reduced for given loading and boundary conditions by carrying out design modifications to the assembly without changing the manufacturing process. It was found that mass has been reduced to 13\% of baseline model and stiffness also increased in all the directions. Modal analysis results indicate that all the natural frequencies are well within the range of baseline model.

Keywords - Radial arm, Optimization, Modal Analysis, Static Analysis

1. Introduction
The radial arms are sheet metal fabricated members that are assembled in a clam shell arrangement. The radial arm is used for supporting the body and dissimilar parts of an automobile. The Fig.1 shows the radial arm assembled in vehicle suspension system. It has to withstand the loads such that the displacement and stresses developed are within permissible limit [1]. The sizing of mesh was chosen according to grid independence test for improved and accurate result. Modal analysis was used to find the natural frequency of the component or assembly. There is some percentage of error in the simulation and analytical methods. To predict the error, stiffness model of the component was built [2].

Fig.1 Radial arm attached to vehicle
The present work includes modal and static analysis of radial arm of an automotive suspension system made from steel and also to carry out the mass optimization of the component. In the study, the radial arm of a four-wheeler automobile was considered for a safe design process, modal and static stiffness analysis. Mass optimization was carried out by performing design modifications in radial arm. All the parameters such as mounting position, bolt position, rivet positions are taken care while modifying the radial arm, so that design modification does not alter the position of these parts. Mass reduction helps in improving the efficiency of the overall system. The Radial arm model was created in Catia V5 and imported to Altair Hypermesh for FE modeling and preprocessing was carried out by applying appropriate boundary and loading conditions. The optistruct solver was used for performing the analysis and Heacview was used for post processing. Further, comparison is made between existing steel radial arm and the optimized model of radial arm in terms of natural frequencies, deflection and stiffness. The simulation results and the key features of the design modified radial arm are discussed in the following section.

1.1 Material Properties
The Table.1 gives the material properties of radial arm used for modal and static structural analysis.

| Property                  | Value       |
|---------------------------|-------------|
| Density                   | 7800 kg/m³  |
| Poisson’s ratio (ν)       | 0.3         |
| Elastic modulus(E)        | 210 GPa     |

2. Cad model of Baseline Radial Arm
The Radial arm model created in Catia V5 is shown in Fig.2. Baseline model of radial arm consist of total 6 parts namely arm, arm rear cover, arm bush, arm stud, bush cover and C bracket as shown in Fig.3 along with materials used and gauge (thickness) properties. Total mass of the radial arm is 10.13 kg.
3. FE Model of Baseline Radial arm

The radial arm CAD model was imported to Altair Hypermesh. The Figure 4 shows the FE model of radial arm where geometry clean-up was performed and extracted the mid surface for all the components. Elements considered for static and modal analysis are 2D- Pshell with four nodded quadrilateral and three noded triangular elements having six degree of freedom at each node [4]. Welding between the components was created by rigid Rbe2 elements. While meshing or FE modeling some of the quality parameters such as warpage, aspect ratio, skew, Jacobean and minimum element sizes are to be maintained.
3.1 Modal Analysis of Radial Arm

Modal analysis is performed to determine the natural frequencies and mode shapes. Using modal analysis, it is possible to observe the characteristic behaviour of the structure and the natural frequency of the component. The rigidity of the component could be analyzed and by knowing natural frequency, the resonance could be avoided. The main features of each mode of the structure can be figured out through the modal analysis and the actual vibration response under this frequency range can be predicted [5]. The results from modal analysis can be used as reference value for other dynamic analysis such as random analysis, harmonic analysis, etc.

Modal analysis was carried out using the Free-Free (without any constraints) boundary conditions. First twelve modes are determined, in that initial 6 modes are rigid body modes and are equal to zero frequency. For the 7th mode natural frequency is found to be 185.5 Hz and the maximum displacement of the chassis is 3.41 mm at that frequency. Similarly, for 12th mode, natural frequency is 1002.2 Hz and the maximum displacement is 2.52 mm. Mode shapes of the baseline model were shown in Figure 5 and related deformation pattern corresponding displacement and natural frequencies were given in table 2.

| Mode Number | Natural frequency (Hz) | Mode shape deformation pattern | Displacement (mm) |
|-------------|------------------------|-------------------------------|-------------------|
| 7           | 185.5                  | X-Bending                     | 34.10             |
| 8           | 268.7                  | Z-Bending                     | 22.06             |
| 9           | 369.4                  | Y-Bending                     | 26.23             |
| 10          | 704.8                  | Twisting                      | 25.76             |
| 11          | 748.4                  | Double Bending in Z-Direction | 48.20             |
| 12          | 1002.2                 | Mixed mode                    | 25.72             |

Table 2 Natural frequencies of the baseline model of radial arm

Fig.5 Different mode shapes of the baseline model of radial arm
3.2 Static Structural Analysis of Radial Arm

Static structural analysis was performed to determine the stiffness of the component at the location for the given loading and boundary conditions [6]. For the analysis, displacement in all the directions are fixed at the hinge location as shown in Figure 6 and at bush location the force of 1000N applied along X, Y and Z directions as shown in Figure 7. The displacement along X, Y and Z direction was found from the analysis. Using the displacement values, the stiffness of the component was determined.

Analysis was carried out in Optistruct solver [7-8]. From the analysis, displacement and stiffness values for baseline model was determined and are presented in the table 3.

| Direction of applied Force | Applied force (N) | Displacement (mm) | Stiffness (N/mm) |
|----------------------------|------------------|-------------------|------------------|
| X                          | 1000             | 0.072             | 13888.89         |
| Y                          | 1000             | 4.624             | 216.26           |
| Z                          | 1000             | 1.666             | 600.24           |

Fig.6 Boundary conditions at hinge location

Fig.7 Loading conditions at Bush location
4. Design Modification
The Design modification (Re-design) is the process of achieving some desired set of specification which minimizes critical factors of the model. While modifying the model, the designer must have the knowledge about model and behaviour of the model under given loading condition [9-11].

In the study, objective is to minimize the displacement of baseline model of radial arm. Therefore, displacement for modified design should be less than that of the baseline design for static analysis. Displacement of radial arm has different standard values for different type vehicle frames and also has different values for different type of analysis. Still it is possible to minimize the deflection of radial arm without increase in the mass of the components [12]. Design modification iterations are carried out by changing back cover design, varying thickness and modified design of C-bracket. Also, by changing number of components and are presented below.

**Iteration1:** The baseline model is modified by gauge properties of two components and one more new component arm cup bracket is added near the stud area. The total no of components in the model are 7.

**Iteration2:** Model of the previous iteration is modified near Arm C bracket and the gauge property of Arm C bracket is increased. The total no of components in the model are 7.

**Iteration3:** Model of the iteration 2 is modified near Arm C bracket and an entire Arm C bracket is removed and the arm cup bracket is newly designed. The total no of components in the model are 6.

Table 4 shows comparison of mass, number of nodes and elements in each model. Table 5 shows design modifications carried out to the baseline model of radial arm.

| Model Description | Baseline Model | Iteration1 | Iteration2 | Iteration3 |
|-------------------|----------------|------------|------------|------------|
| Mass (kg)         | 10.13          | 8.099      | 8.93       | 8.93       |
| No of components  | 6 Parts        | 7 Parts    | 7 Parts    | 6 Parts    |
| Total Number of Nodes | 12641       | 22368      | 22464      | 23116      |
| Total Number of elements | 12350        | 20939      | 22170      | 22793      |

| Sl No | Baseline Model | Iteration-1 | Iteration-2 | Iteration-3 |
|-------|----------------|-------------|-------------|-------------|
| 1     | 6 Parts        | 7 Parts     | 7 Parts     | 6 Parts     |
|       | Thickness (mm) | 5.0         | 3.5         | 3.5         | 3.5         |
| 2     |               |             |             |             |
|       | Thickness (mm) | 5.0         | 3.0         | 3.0         | 3.0         |
| 3     |               |             |             |             |
|       | Thickness (mm) | 1.5         | 1.5         | 1.5         | 1.5         |
The modal analysis is carried out for all modified designs and natural frequencies are determined [13-14]. Natural frequencies of 7th to 12th modes are listed in the Table 6.

Table 6: Natural frequencies of modified designs

| Mode Number | Natural frequency (Hz) |
|-------------|------------------------|
|             | Baseline Model | Iteration-1 | Iteration-2 | Iteration-3 |
| 7           | 185.5          | 225.1        | 222.1        | 223.1        |
| 8           | 268.7          | 320.5        | 306.1        | 308.4        |
| 9           | 369.4          | 514.7        | 506.1        | 505.4        |
| 10          | 704.8          | 545.4        | 744.2        | 582.4        |
| 11          | 748.4          | 754.5        | 763.3        | 758.4        |
| 12          | 1002.2         | 776.0        | 797.1        | 801.0        |

Natural frequencies and mode shapes of 7th to 10th modes of baseline and all the modified designs of the radial arm are shown in Figures 8-11. Figure 8 shows the 7th mode of all the iterations, Figure 9 shows the 8th mode, Figure 10 and 11 shows the 9th and 10th mode for all the iterations respectively. From the modal analysis, it is observed that all the frequencies are well within the range of baseline model that is from 185 Hz - 1000 Hz.
Fig. 8 Modal parameters for baseline and modified designs of the radial arm at 7th mode

Fig. 9 Modal parameters for baseline and modified designs of the radial arm at 8th mode

Fig. 10 Modal parameters for baseline and modified designs of the radial arm at 9th mode
The static structural analysis was carried out for modified designs using same loading and boundary condition as of Baseline model and the results for the displacement and stiffness in X, Y and Z directions are presented in the Table 7.

| Displacement in mm | Baseline Model | Iteration-1 | Iteration-2 | Iteration-3 |
|-------------------|----------------|-------------|-------------|-------------|
| X                 | 0.072          | 0.067       | 0.052       | 0.0531      |
| Y                 | 4.624          | 4.405       | 3.684       | 3.579       |
| Z                 | 1.666          | 1.776       | 1.651       | 1.574       |

| Stiffness in N/mm | Baseline Model | Iteration-1 | Iteration-2 | Iteration-3 |
|-------------------|----------------|-------------|-------------|-------------|
| X                 | 13888.89       | 14925.37    | 19230.77    | 18832.39    |
| Y                 | 216.26         | 227.01      | 271.44      | 279.41      |
| Z                 | 600.24         | 563.06      | 605.69      | 635.32      |

The Figures 12-14 shows the displacement of the radial arm in X, Y and Z loading direction respectively. From the result, it is found that the stiffness increased in all the direction in iteration-3 model.
Fig. 12. Displacement and stiffness of the radial arm in X direction loading

Baseline
- Displacement in X-Direction mm: 0.072
- Stiffness in N/mm: 13888.89

Iteration-1 Model
- Displacement in X-Direction mm: 0.067
- Stiffness in N/mm: 14925.37

Iteration-2 Model
- Displacement in X-Direction mm: 0.052
- Stiffness in N/mm: 19230.77

Iteration-3 Model
- Displacement in X-Direction mm: 0.0531
- Stiffness in N/mm: 18832.39

Fig. 13. Displacement and stiffness of the radial arm in Y direction loading

Baseline
- Displacement in Y-Direction mm: 4.624
- Stiffness in N/mm: 216.26

Iteration-1 Model
- Displacement in Y-Direction mm: 4.405
- Stiffness in N/mm: 227.91

Iteration-2 Model
- Displacement in Y-Direction mm: 3.684
- Stiffness in N/mm: 271.44

Iteration-3 Model
- Displacement in Y-Direction mm: 3.579
- Stiffness in N/mm: 279.41
5. Conclusions

- In the present work mass optimization, modal and static structural analysis of radial arm was carried out. Natural frequencies and mode shapes of the optimized design of radial arm were determined and compared with baseline model. The following observations were made from the analysis.
  - Modal analysis was carried out to determine natural frequency of baseline and modified design models of radial arm, which is significant to study the vibrational characteristics and to avoid resonance. It is found that the natural frequencies of iteration 3 model are comparable with baseline model results.
  - From the static structural analysis, it is found that the deformation of the radial arm is reduced from 0.072 mm to 0.053 mm in X direction, 4.624 mm to 3.579 mm in Y direction and 1.666 mm to 1.574 mm in Z direction by design modification for iteration 3 model.
  - The Stiffness is increased by 26, 23 and 6 % along X, Y and Z direction for iteration 3 model.
  - Design modifications are carried out in radial arm to optimize the mass and there is a net reduction of 13% in radial arm mass due to design modification.
  - From modal and static analysis, it is found that the iteration-3 model satisfies all the design requirements compared to baseline model. Therefore, iteration-3 model can be used for further design development and studies related to durability and fatigue analysis are to be carried out before taking up for manufacturing the product.

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