Design Study of an Electric Motorcycle Chassis Obtained using Topology Optimization

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Abstract. Rising Carbon emission and associated pollution forcing government of India to make stringent emission norms and policies. Hence, it is need of the hour to switch to alternative fuels such as electricity. About 60% of the petrol consumption in India is attributed to the motorcycles and there hasn’t been significant research in the electric mobility in motorcycles. This work is based on study of an electric motorcycle chassis with integrated battery-pack space that has been obtained as a conceptual geometry using topology optimization. The layout of the chassis for this work has been obtained by applying topology optimization on a design domain representing a space obtained on the basis of presently available dimensional measurements of commuter segment motorcycles in India. The chassis has been subjected to linear static and modal analysis for further enhancing the strength, stiffness and natural frequency using the design study approach on critical region.

1. Introduction

Chassis, also known as frame is the support framework that bears static and dynamic loads acting on the vehicle. Its design plays critical role in vehicle performance, rider comfort, steering quality, handling etc. Kurdi et al. used FEM to analyse stresses in truck chassis [1]. They have stressed on predicting fatigue life of the chassis and durability loading in its designing so as to verify safety during its use in real life situations. Also, they have shown that the critically stressed zones in the chassis due to loading must be located using FEM because such regions are the first points of fatigue failure propagation. Jonathan Hastie et al. have studied the front and side impacts and loading due to shock mounts on SAE BAJA vehicle [2]. It helped them in modifying the chassis by adding three key structural components to bear the loading conditions. It was also found out that the design failure occurred in roll over and hence an integrated solution from the beginning could be proposed using the FEA methodology.

Four repetitions of analysis have been studied by Bennett et al. for designing a frame [3]. They applied simple load cases to various frames and the one with highest factor of safety (FOS) was considered for further analysis such as side impact, drop test etc. In order to reaffirm ability of the vehicle to endure extreme loading conditions, Raina et al. have analyzed the frame with considerable
factor of safety (FOS) [4]. This was done so as to validate the frame to withstand loading and minimize the chances of failure and the risks arising out from it.

Topology Optimization is an optimization technique that helps in finding the most efficient material distribution in a design domain, that can withstand externally applied loads. The last few decades have seen significant application of this technique in addressing structural problems using FEA, especially in the automotive industry. Topology optimization and topography optimization have been combined and has been used to design a contact start-stop suspension system subject to various frequencies such as torsional, bending and sway modes by Kilian et al. [5]. Chiandussi et al. have used topology optimization on automotive suspension [6]. In it, the suspension system was subjected to three static loads under volume constraint and minimum compliance. Similarly, Chang and Lee have applied topology optimization on a bracket used in automotive air conditioner subject to minimum compliance design and natural frequency constraints [7]. Wang et al. optimised the thickness and distribution of material reinforcements and thereby improved the stiffness of an automobile body using size and topology optimizations [8]. Pederson et al. in his work studied a crushed structure and its energy absorption history using topology optimization [9-10]. Jeyapandiarajan et al. have done a comparison between various materials by comparing stress, deformation and FOS to design the chassis for an electric two-wheeler using FEA [11]. They have shown a compromise in terms of material strength and cost of manufacturing for the chassis. Gazaly has observed the suitability of common FEA tools in studying stress analysis [12]. He has analysed stress and deformation of a truck chassis using four FEA tools viz., Ansys, Abaqus, Hyperview and Nastran. He has also found out that Ansys and Abaqus to be most frequently used FEA packages in such studies.

Furthermore, the vibration characteristics including the mode shapes and natural frequencies of a truck chassis have been studied by Fui et al. [13]. Observations regarding displacement and stress distribution of the chassis under different boundary conditions has been made using finite element technique. Also observation that road irregularity causing excitation to the truck chassis is the main disturbance to the frame and that various mounting locations of the components can be altered based on mode shape response. He has also suggested some modifications in order to reduce vibration and improve stiffness of the chassis. A hybrid prototype of an electric motorcycle using an effective and compact powertrain has been designed by Stuecke et al. [14]. The prototype has been designed by altering the original machine with minimal changes, such that high performance is achieved without increasing the overall weight of the chassis significantly. For example, the electric components have been mounted in such a way that original shape and aerodynamics of the vehicle has been retained.

The development in electric vehicle has gained tremendous pace in the past few years, especially due to reduction in the prices of power storage battery packs and various incentives offered by the governments across the globe. Topology optimization as a tool to design automotive components has also been used extensively in the recent past, but Stefanos et al. has applied nested topology optimization to design the chassis for an electric two-wheeler, combining the structural applicability of the tool with the positioning of battery pack space within the design domain [15]. Also, recently Airbus APWorks developed an electric motorcycle by combining the study and the manufacturing process (additive manufacturing) [16]. The frame weighed as low as 6kg and the entire motorcycle weighed less than 35kg. This work has taken inspiration from the research work that has been under progress in designing innovative and novel chassis for a motorcycle segment that will cater to largest proportion of masses in the two-wheeler industry.

2. Methodology of Study
The conceptual geometries were obtained using topology optimization (level-set algorithm) applied to the design domain developed for commuter segment motorcycles presently available in India. The geometries obtained from topology optimization were used to generate 15 possible conceptual design of the chassis. The mode shapes have been utilised to find the optimal parameters of the chassis such as pipe diameter, thickness, tube width and height, keeping wheelbase constant for all purposes. The analysis has been done by subjecting the model to three different loading conditions i.e., for maximum
braking at front axle, maximum acceleration at rear wheels and lateral load when motorcycle is on curve within limits of pneumatic adherence.

The work has involved FEA to assess the validity of the chassis when used on real life electric motorcycle. The preliminary stage involved data collection of the current commuter segment motorcycles in India. Various dimensions of the motorcycles such as length, width, seat height, ground clearance etc. were utilised to design the control volume (design domain) as shown in Figure 1, on which topology optimization was performed using Autodesk’s Fusion 360™. The volume of the design domain was such that it could accommodate as much space as required to cover the chassis of the electric motorcycle. Boundary conditions based on which topology optimization was performed is beyond the scope of this paper. The results obtained by topology optimization have been used as the basis of the design of the chassis.

![Figure 1. Side view and Front view of the commuter motorcycle and associated dimensions.](image)

Table 1 shows the technical specifications and geometric dimensions based on which the control volume for the chassis has been developed. These dimensions have been taken as average value of individual dimensions of the commuter segment motorcycles.

| Sr. No. | Parameter          | Specification (mm) |
|---------|--------------------|--------------------|
| 1       | Wheelbase          | 1367               |
| 2       | Ground clearance   | 169                |
| 3       | Seat height        | 793                |
| 4       | Length             | 2013               |
| 5       | Width              | 748                |
| 6       | Overall Height     | 1081               |

The CAD model has been prepared keeping in mind manufacturability using Solidworks2019®. The CAD model of the chassis was analyzed for stresses and mode shapes using Altair HyperWorks and further design study was carried out. The Figure 2 represents the flowchart of the process applied in the study.
2.1. Design Domain generation and Meshing
The design domain in this study represents a volumetric space of material that covers the entire region occupied by the chassis of commuter segment motorcycles. Hence, for the purpose, the dimensions for the design domain have been drawn from the existing motorcycle chassis and meshed with 34471 solid Hexahedron elements of size 10mm for application of the topology optimization. The volume occupied by the battery space has been cut out from the design domain and has been geometrically restricted in order to avoid any optimization in that region. Figure 3 depicts the process for the same.

2.2. Topology Optimization results and development of roll-cage type manufacturable chassis
The results of topology optimization have been used as the basis for designing the chassis. Topology Optimisation has been performed using targets for 80% volume reduction and stiffness maximisation using level-set algorithm and stereolithographic file (.stl) was promoted to generate the layout of the frame as shown in Figure 4. Using the final layout, CAD model was developed using tubular sections such that manufacturability improves.
3. Design Study based on Stress Analysis Results

3.1 Boundary Conditions and Mesh

As loads are calculated for three situations viz. for extreme braking at front wheels, extreme acceleration at rear wheels and lateral load under pneumatic adherence limits on the curves, for the purpose of design study load due to extreme braking have been considered as the values are much higher than that of the other cases. Single point constraint is applied at the swing arm pivot hole of the chassis and point loads act on the headstock as shown in Figure 5. The chassis has been meshed on the mid-surface with 2D elements of size 5mm and quads and trias totaling 37723 elements in numbers.

3.2 Mode Shapes, Natural Frequency and Stress analysis (1st iteration)

Natural frequency has been used as the criteria to inspect the feasibility to manufacture the chassis. Deflection result has been used to add elements around the stressed zones. Figure 6 to Figure 9 represent the results obtained from the first iteration of the design study.

3.2.1 Mode Shapes

(a) First order mode, 2.33Hz    (b) Second order mode, 4.62 Hz    (c) Third order mode, 6.93Hz

Figure 6. Natural frequency and modal analysis results upto third order mode.
(a) Fourth order mode, 12.56 Hz        (b) Fifth order mode, 14.92 Hz      (c) Sixth order mode, 19.73Hz

**Figure 7.** Natural frequency and modal analysis results from fourth to sixth order mode.

### 3.2.2 Maximum stress

(a) Max braking at front axle    (b) Max acceleration at rear axle   (c) Pneumatic adherence limit curve

**Figure 8.** Stress induced under three loading situations.

### 3.2.3 Maximum Deflection

(a) Max braking at front axle    (b) Max acceleration at rear axle   (c) Pneumatic adherence limit curve

**Figure 9.** Deflection of chassis under loading condition.

A brief observation leads to the understanding that the natural frequency of the chassis for the first six mode shapes are way too low to actually build one. In fact, the natural frequency in the second and third modes coincides with human body’s natural frequency and that would cause discomfort to the rider in the real life scenarios. In order to improve its performance, most stressed region is identified at the bottom portion joint and two parallel tubes are added to it. The modified chassis is again analyzed for its behavior and have been shown in Figure 10 to Figure 13 as the results obtained from the second iteration of the design study.
3.3 Mode shapes, Natural frequency and Stress analysis (2\textsuperscript{nd} iteration)

3.3.1 Mode shapes and corresponding natural frequencies

(a) First order mode, 29.44Hz      (b) Second order mode, 58.02Hz      (c) Third order mode, 69.83Hz

\textbf{Figure 10.} Natural frequency and modal analysis results up to third order mode.

(a) Fourth order mode, 133.46Hz      (b) Fifth order mode, 182.45Hz      (c) Sixth order mode, 205.6Hz

\textbf{Figure 11.} Natural frequency and modal analysis results from fourth to sixth order mode.

3.3.2 Maximum stress

(a) Max braking at front axle      (b) Max acceleration at rear axle      (c) Pneumatic adherence limit curve

\textbf{Figure 12.} Stress induced under three loading situations.

3.3.3 Maximum deflection

(a) Max braking at front axle      (b) Max acceleration at rear axle      (c) Pneumatic adherence limit curve

\textbf{Figure 13.} Deflection of chassis under loading condition.
As it can be seen that there is significant improvement in natural frequencies, that is now on the acceptable levels of manufacturability (approximately four-fold above that of human body). But the deformation needs to be constrained to lower values. Hence, an additional third tube is added as a connection to the swing-arm pivoting hole tube with increased thicknesses of all the three elements. The whole procedure is re-analyzed as shown in Figure 14 to Figure 17 as results obtained from the third iteration of the design study.

3.4 Mode shapes, Natural frequency and Stress analysis (3rd iteration)
3.4.1 Mode shapes and corresponding natural frequencies

![Mode shapes](image)

(a) First order mode, 38.59Hz  (b) Second order mode, 61.89Hz  (c) Third order mode, 70.60Hz

**Figure 14.** Natural frequency and modal analysis results upto third order mode.

![Mode shapes](image)

(a) Fourth order mode, 133.46Hz  (b) Fifth order mode, 182.45Hz  (c) Sixth order mode, 205.6Hz

**Figure 15.** Natural frequency and modal analysis results from fourth to sixth order mode.

3.4.2 Maximum Stress

![Stress](image)

(a) Max braking at front axle  (b) Max acceleration at rear axle  (c) Pneumatic adherence limit curve

**Figure 16.** Stress induced under three loading situations.
3.4.3 Maximum Deflection

Figure 17. Deflection of chassis under loading condition.

Addition of parallel tubes on the lower region of the chassis helped in enhancing the stiffness as well as increased the natural frequency to permissible levels which are safe for the riders use. Table 2 shows a comparison of the natural frequencies vis-à-vis mode numbers.

| Mode Number | Natural Frequency (Hz) (First Iteration) | Natural Frequency (Hz) (Second Iteration) | Natural Frequency (Hz) (Third Iteration) |
|-------------|------------------------------------------|--------------------------------------------|------------------------------------------|
| 1           | 2.33                                     | 29.44                                      | 38.59                                    |
| 2           | 4.62                                     | 58.02                                      | 61.89                                    |
| 3           | 6.93                                     | 69.83                                      | 70.60                                    |
| 4           | 12.56                                    | 133.46                                     | 138.04                                   |
| 5           | 14.92                                    | 182.445                                    | 187.18                                   |
| 6           | 19.73                                    | 364.68                                     | 208.30                                   |

For the sake of clarity, a graphical representation for the stress and deflection for the three load cases, i.e. when maximum braking is applied to front wheels, when maximum acceleration occurs at rear wheels and when the vehicle is on curves subject to pneumatic adherence limits has been presented in Figure 18. The maximum stress and deflection have reduced as the stiffness improved.

4. Conclusion

This study has been conducted to design a novel chassis for an electric motorcycle using numerical methods and CAD tools. The mode shapes and corresponding natural frequencies helped modifying the chassis in such a way that its stiffness increased significantly thereby reducing deflections at critical points. It was witnessed that addition of two parallel tubular elements at the base region of the chassis helped increase the first natural frequency from 2.33Hz to 29.44Hz. Further addition of a parallel element at the central portion just above the swing-arm pivot hole with increased pipe
thickness led to improved natural frequency to 38.39Hz. As normal sustainable human body natural frequency lies in the range of 5Hz to 7Hz with the present situation is very safe and comfortable for the riders. Also the maximum stress and deflection reduced from 810 MPa to 181 MPa and 25.4mm to 1.85mm respectively for the first load case of maximum braking at front wheels, from 628 MPa to 12 MPa and from 10.4mm to 1.58mm respectively in the second load case of maximum acceleration at rear wheels and from 224 MPa to 11.8 MPa and 3.8mm to 0.271mm respectively in the third load case of pneumatic adherence limit on curves. With the considerably reduced induced stresses and deflection, the electric motorcycle chassis is safe and easily for fabrication. This study has revealed the importance of design study before fabrication of final chassis designs. It primarily enhances the safety of the rider due to increased stiffness and secondarily as a compromise between weight and stiffness, as further addition of elements would only make the chassis heavier.

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