Light-weighting of single-sided motorcycle swing-arm through generative design

Adarsh Balasubramanian1, G Shaktivel2 and N Raghukiran3

1,2,3Centre for automation, School of Mechanical Engineering, Vellore Institute of Technology, Chennai Campus, Tamil Nadu, India

adarsh.balasubramanian2018@vitstudent.ac.in1, sakthivel.g@vit.ac.in2, raghukiran@vit.ac.in3

Abstract. This work explores the prospects of Generative Design to generate the single-sided swing-arm of a homologated motorcycle to perform the process of light-weighting by selecting two aluminum alloys, namely Al 6061 (primary) and Al 7075 (reference), as materials and 5-axis milling as the manufacturing method. This work also cites and summarizes a couple of previous studies to establish the findings that Al 7075 is a superior material for the manufacturing of the single-sided swing-arm when compared to steel and further proceeds to expatiate as to why Al 6061 should be considered as opposed to Al 7075 for increased gains from the process of light-weighting with substantiations from the analysis of the single-sided swing-arm under the simulated loads.

Key Words. Generative Design, Additive Manufacturing, Optimization, Automobile Engineering, 3D modeling.

1. INTRODUCTION

Motorcycles are one of the most affordable and most common modes of transport for many people around the world. Yet some motorcycles are homologations of purpose-built race motorcycles available to the public. These homologated motorcycles are loaded with the latest advancements in technology and sciences making them a road-legal version of their racing counterpart. One of the main characteristics of these motorcycles is that they are extremely light. Being extremely light, these motorcycles emit lesser pollution and have a lesser gross carbon footprint when compared to other traditional motorcycles as they consume lesser material and lesser fuel. This inference is substantiated [1] as it analyses the savings in energy and the reduction in emissions of vehicles using lightweight materials.

With automobile emissions contributing to global warming, automobiles must be as efficient as possible. The two main areas where major gains could be realized are the IC engine and material usage. With the maximum thermal efficiency achieved at about 50% [2] and further gains in the thermal efficiency of the
IC engines becoming increasingly expensive, manufacturers have resorted to the process of light-weighting to further optimize their vehicles. The process of light-weighting is axiomatic in the sense that manufacturers aim to achieve the lightest weight possible for each component while still maintaining and enhancing its intended purpose. Two major ways through which this is done are Topology Optimization and Generative Design. As there are numerous pieces of literature elucidating the principles and the application of Topology Optimization, this study focuses on the prospects of Generative Design [3,4]. If the process is estimated to be too expensive to be carried out for the entire automobile, it is implemented for the critical components as they offer the major gains. One such critical component is the swing-arm (as inferred from [5-7]), because it characterizes the behavior of the motorcycle as it regulates the interaction of the rear wheel with the road through a system of springs and dampers by connecting the rear wheel to the main chassis. There are two basic designs of the swing-arm that are in use today, namely single-sided swing-arm and double-sided swing-arm. Single-sided swing-arm is preferred over double-sided swing-arm motorcycles as it provides greater ease of access to the suspension system, chain assembly, brake assembly, and the wheel assembly, which helps with the maintenance of the motorcycle with minimal effort.

There are numerous types of single-sided swing-arms available in the market today most of which are manufactured through the standard process of welding multiple pieces together to create the swing-arm. This study focuses on the generation of the single-sided swing-arm as a single component through the process of Generative Design for maximum light-weighting and analysis of its performance against simulated forces.

Generative Design is an iterative design process that involves a program and a designer where the program, mainly originating from nature-mimicking procedures, generates a certain number of outputs that meet certain constraints while acknowledging user-defined criteria and limitations and the designer which can be either an algorithm or a human that fine-tunes the feasible region by changing minimal and maximal values of an interval in which a variable of the program meets the set of constraints, to reduce or augment the number of outputs to choose from.

2. MATERIALS SELECTION AND MODELLING

Almost all components of an automobile are made from alloys. This is because alloys offer a plethora of advantages over pure metal which includes increased strength and increased corrosion resistance. Aluminum alloys, especially, are used extensively as opposed to other alloys because they offer the fastest, safest, most environmentally friendly, and cost-effective way for increased performance and fuel economy while maintaining or enhancing safety and durability with reduced emissions.

2.1. MATERIAL SELECTION

Aluminum is 10% - 40% lighter than steel depending on the product, yet possesses significant malleability allowing engineers to design and manufacture shapes optimized for maximum performance. Automobiles manufactured from aluminum components are about 24% lighter than those made from steel and save about 0.7 gallons per 100 miles, which is a saving of about 15% in fuel consumption. These automobiles also have better acceleration, better braking, and better handling by virtue of the rigidity possessed by aluminum components which provides immediate and precise control to the driver. This study focuses on two aluminum alloys, namely Al 7075 and Al 6061. Al 6061 is considered as the primary alloy for the machining of the single-sided swing-arm and for analysis under simulated loads, while Al 7075 is
considered as reference material because there is numerous literature exploring the performance of the single-sided swing-arm made from it and hence provides valuable reference points [4,5,8].

Al 7075 is an aluminum alloy with zinc as the primary alloying element. It has excellent mechanical properties and exhibits good ductility, high strength, toughness, and good fatigue resistance. However, it is more susceptible to embrittlement than many other aluminum alloys because of micro-segregation but has significantly better corrosion resistance. Al 6061 is a precipitation-hardened aluminum alloy, containing magnesium and silicon as its major alloying elements. It has very good corrosion resistance and very good weldability although reduced strength in the weld zone. It has medium fatigue strength and good cold formability. It is one of the most commonly used alloys of aluminum for general-purpose use.

Table 1. Mechanical Properties of Al 6061 & Al 7075

| S. No | Properties          | Al 6061 (MPa) | Al 7075 (MPa) |
|-------|---------------------|---------------|---------------|
| 1     | Density             | 2700 Kg/m³    | 2810 Kg/m³    |
| 2     | Young’s Modulus     | 68.9 GPa      | 71.7 GPa      |
| 3     | Poisson’s Ratio     | 0.33          | 0.33          |
| 4     | Ultimate Tensile    | 310 MPa       | 572 MPa       |
| 5     | Tensile Yield Strength | 276 MPa   | 503 MPa       |

Al 6061 is chosen for study because of its ease of fabrication compared to Al 7075. This is mainly due to Al 6061 alloy’s lower hardness and tensile strength. The relatively lower hardness allows it to be machined more easily than Al 7075.

2.2. MODELLING AND MANUFACTURE OF SWING-ARM

MODELLING OF SWING ARM

An open-source CAD file of a homologated racing motorcycle is selected for this study. The essential components required for generative design studies such as frame, swing-arm pivot, linkage mount, axle blocks, wheel assembly, suspension linkage, mono-shock, footrest on the frame, engine block, and the chain assembly are isolated from the rest of the components for ease of work. These isolated components are termed Derived components. These derived components have to be classified as either preserved regions or as obstacle geometries.

The “Preserve regions” are those regions that are maintained and form the base from which additional geometries are created by the generative design algorithm i.e., these are regions that form a part of the final generated component. In this study, these are the swing-arm pivot, linkage mount, and axle block components. “Obstacle geometries” are those regions that are to be avoided and the algorithm has to build around these regions i.e., these are regions that do not form a part of the final generated component. In this study, these are the wheel assembly, suspension linkage, mono-shock, footrest on the frame, engine block, and the chain assembly components. The Preserve regions (green) and the Obstacle geometries (red) are illustrated in Figure 1.
2.2.1 GENERATIVE DESIGN PARAMETERS

Once the preserve regions and the obstacle geometries are precisely defined, the study resolution is to be determined. The study resolution indicates the size of the mesh elements to be created. The coarser the mesh, the coarser the result is going to be. Because this study deals with a fairly complex part, the study resolution is set to the finest allowable limit. This ensures a fairly smooth output. Once the study resolution is defined, the materials for the study are selected. Aluminum alloys Al 6061 and Al 7075 are selected as study materials. These two aluminum alloys were selected over steel because other works have averred the superiority of Al 7075 over steel and the focus of this study is to assert that Al 6061 is a better material than Al 7071, for the manufacture of the swing-arm, on the account of gains achieved from light-weighting [4,5].

Characteristics such as deformation, stress developed, factor of safety, and weight are contrasted between materials Al 7075 and AISI 1020 steel [5]. It is observed from the literature that, despite having similar stress developed, the swing-arm made from Al 7075 deflects significantly less (about 71% lesser), has a higher factor of safety (about 18% more), and is significantly lighter (about 64% lighter) when compared to the swing-arm made of Steel. Hence the literature concludes that Al 7075 is an optimal material for the fabrication of the swing-arm.

A topology optimized swing-arm made from Al 7075 is compared to a standard swing-arm made from AISI 1010 steel [4]. It is observed from the literature that the swing-arm made from Al 7075, despite the weight reduction of about 44%, had significantly lower stress developed (up to 21% lesser), a notable increase in factor of safety, and significantly lower deflection. Hence, the literature concludes that the swing-arm made from Al 7075 is quite safe under static running conditions.

MANUFACTURE OF SWINGARM:

Components of a motorcycle have to be stiff to support the mass and transfer loads with minimum losses. Losses usually occur when the component deforms under load. This is extremely undesirable and dangerous because it is extremely difficult to predict the behavior of a deformed component and might cause unpredictable failures. These components also have some amount of flex in them in certain directions. This is because the components have to sustain various vibrations generated while the vehicle is in motion. If enough flex is not provided, the components might fracture/snap under these immense
vibrations. This is especially serious in the case of critical components such as swing-arms, suspension rods, etc. Hence for this study, the swing-arm of the motorcycle doesn’t have to be as rigid as possible and can have a limited amount of flex.

Once the materials are assigned, the study objectives are determined. The study objectives include the factor of safety (or safety factor) and the manufacturing method. The safety factor is a measure of the strength of the system that expresses how much stronger a system is than it needs to be for an intended set of loads. A target safety factor of 2 is set for this study. There are a plethora of manufacturing processes to choose from, but the two main processes under consideration are Additive Manufacturing and Milling. Since this is a fairly complex component, there would be increase preprocessing and postprocessing steps involved in the case of Additive Manufacturing. The volume of the component, because it needs to be created as a single component, would also prove as a deterrent for the additive manufacturing process. Hence this study focuses on the manufacturing of this part through milling. Due to the extreme complexity and the intricate nature of the part, the 5-axis milling is assigned as the manufacturing method.

3. DESIGN CALCULATIONS

Once the manufacturing method is defined, the constraints and loading conditions are defined. These are vital for the generation of the component because they help in the analysis of the component during the simulation and ensure that the component functions as intended.

3.1. WEIGHT AND LATERAL LOADING

The curb weight of the motorcycle is 250 kg and considering only one person (average weight of 75 Kg) is riding the motorcycle, the dead-weight of the motorcycle is 325 Kg. The weight distribution ranges from 58% - 65% on the rear axle in most motorcycles. Hence for this model, the weight distribution is taken to be 60% on the rear axle.

The net load on the rear axle of the motorcycle is

$L_S = 0.6*(M_T + M_P) = 0.6*(250+75) = 195$ Kg.

This load will be distributed on the single side of the swing-arm and will be acting at the damper at an angle of 88°. Thus, the vertical and horizontal components of the load are

Vertical load ($L_{VS}$) = $L_S \sin\theta = 195*9.81*\sin(88°) = 1911.8$ N

Horizontal load ($L_{VH}$) = $L_S \cos\theta = 195*9.81*\cos(88°) = 66.8$ N

The maximum acceleration on the motorcycle was found to be 5.5 m/s² and with a total mass ($M_S$) = 325 Kg, the longitudinal force acting on swing-arm is,

$F_A = M_S \times \text{accl}^n = 325*5.5 = 1787.5$ N
The maximum deceleration on the motorcycle was found to be -6 m/s².
\[ F_B = M_s \times \text{decel} = 325 \times -6 = -1950 \text{ N} \] (Negative sign indicates force acting on the opposite direction)

3.2. CORNERING CONDITIONS
Cornering conditions are one of the most important criteria during the design of an automobile as different components are subjected to loads of different magnitudes acting in different directions. In the case of the swing-arm, high lateral forces act in an unbalanced state whose magnitude of variation depends on the angle of inclination and the speed of the motorcycle. It is assumed that 20% more load will be transferred to the inner side of the swing-arm while navigating a corner and hence the inner side of the beam has to have 70% of the total weight and the outer side of the beam will have the remaining 30%. A maximum lean angle of 40° is considered for cornering conditions. The forces, when divided into vertical and horizontal components, lead to a torsional and lateral imbalance in the middle part.
Thus, 70% of the total weight is

\[ F_{\text{MAX}} = 0.7 \times M_s \times g = 0.7 \times 325 \times 9.81 = 2231.8 \text{ N} \]

And the remaining 30% is

\[ F_{\text{MIN}} = 0.3 \times M_s \times g = 0.3 \times 325 \times 9.81 = 956.5 \text{ N} \]

Horizontal components (acting as lateral imbalance):

\[ F_{\text{BH}} = F_{\text{MAX}} \cos \theta = 2231.775 \times \cos(40^\circ) = 1709.6 \text{ N} \]
\[ F_{\text{OH}} = F_{\text{MIN}} \cos \theta = 956.4750 \times \cos(40^\circ) = 732.7 \text{ N} \]

Vertical components (acting as torsional imbalance):

\[ F_{\text{IV}} = F_{\text{MAX}} \sin \theta = 2231.775 \times \sin(40^\circ) = 1434.6 \text{ N} \]
\[ F_{\text{OV}} = F_{\text{MIN}} \sin \theta = 956.4750 \times \sin(40^\circ) = 614.8 \text{ N} \]

Figure 4: Von Mises Stress developed while navigating Left Turn (a) and Right Turn (b).

4. RESULTS AND DISCUSSIONS

4.1. SOLVING A GENERATIVE DESIGN STUDY

The core mechanism of Generative Design is a level set approach to topology synthesis. Level set methods, by their nature, use the surface area as their main acting stage. This means that changes in surface area to the starting shape (whether created by the solver or specified by the user) will alter both performance and outcomes. The solver inside generative design can explore a much larger design space than a traditional topology optimization system as it is currently based on linear-static FEA methods. By leveraging complex or exotic starting shapes and sizes, the design space can be expanded into new territories (all of which are based on the same problem but with varying starting shapes). The generative design study and analysis are carried out using AUTODESK Fusion 360. In this study, the design is fairly complex as the solver has to build around the prescribed obstacle regions. Owing to the complexity, the process of exploring all design facets is fairly time-consuming.
4.2. COMPARING OUTCOMES AND SELECTING APPROPRIATE GENERATED DESIGN

Once the outcomes are generated, the critical properties such as volume, mass, maximum permissible deflection, and the max permissible Von misses stress are compared between both the swing-arms. The critical properties are those properties that are of interest in the process of light-weighting.

Table 2. Properties Comparison of swing-arm components generated from Al 6061 and Al 7075

| Component | Material       | Volume (mm$^3$) | Mass (kg)       | Max permissible Von Mises Stress (MPa) | Maximum permissible displacement (mm) | Guideline safety factor |
|-----------|----------------|----------------|----------------|---------------------------------------|--------------------------------------|-------------------------|
|           | Aluminum 6061  | 1.06e+6        | 2.9            | 137.5                                 | 5.67                                 | 2                      |
|           | Aluminum 7075  | 1.88e+6        | 5.3            | 72.5                                  | 2.04                                 | 2                      |

The properties of both the swing-arm components generated from Al 7075 and Al 6061 are tabulated and the critical properties are highlighted.

It can be observed from the table that the component generated from Al 6061 is 45.7% lighter, 43.5% smaller than the component generated from Al 7075, and allows a max deformation up to 5.67mm. This is illustrated by Figure 5.
Figure 5: Comparison of physical properties of generated components. It can also be observed from the table that, by virtue of having a greater permissible von mises stress limit, the component made from Al 6061 is stronger than the component made from Al 7075. This is illustrated as a graphical representation by Figure 6. The max permissible von mises stresses were derived from the volumetric analysis of the components made from Al 6061 and Al 7075. The increase in permissible von mises stress limit in the component generated from Al 6061 is attributed to its increased complexity and organic nature when compared to the component generated from Al 7075. This is because of the better formability possessed by the aluminum alloy Al 6061 as it has a lower hardness and a lower tensile strength compared to the aluminum alloy Al 7075.

The increased complexity and the enhanced organic nature of the component generated from Al 6061 ensure that it loads each of its support members along their strongest axis and allows the stress generated under loading to spread more effectively along its body, thus reducing the stress concentration developed at any particular point as opposed to the component generated from Al 7075. Hence, the component generated from Al 6061 can withstand higher loads before failure, making it stronger than the component generated from Al 7075.

Figure 6: Comparison of Max permissible Von Mises Stress in the generated components.

Predicting on the above statements and observations from Table 2 and Figure 6, it is concluded that the component made from Al 6061 is around 89.7% stronger than the component made from Al 7075, thus making the aluminum alloy Al 6061 a superior material than the aluminum alloy Al 7075 for the manufacture of single-sided swing-arm.

4.3. COMPONENT GENERATION

Based on what is inferred from the table and graphs presented above, it is agreed that the swing-arm should be made of Al 6061. Since there are a few modifications to be done before the design could be machined, the Al 6061 outcome is exported as a component (Figure 7). These modifications include making slots for mounting the wheel assembly and a small change in the surface geometry of the linkage mount to allow for ease of movement under load.
The modifications to the component geometry and the meshing are done before the analysis. This is illustrated in Figure 8. The analysis is carried out on the single-sided swing-arm component made from Al 6061 based on the calculations presented under “DESIGN CALCULATIONS”

After the analysis, it is observed that the stresses developed under simulated loads were within the maximum permissible Von Mises Stress.

The Von Mises Stress developed under
i. Lateral Loading conditions are illustrated by Figure 2 for acceleration and by Figure 3 for deceleration.
ii. Cornering conditions are illustrated in Figure 4.

Figure 9 illustrates the observation that the maximum stress developed in the swing-arm component made from Al 6061 was 99.1 MPa under the simulated condition of navigating a left turn, as opposed to the maximum allowable stress of 137.5 MPa.
4.4. SAFETY FACTOR AND DEFORMATION

Factor of safety (or) safety factor indicates how much stronger apart is that it needs to be. A safety factor of 1 indicates that any loads exceeding the simulated value will cause failure to the component subjected to those loads. Likewise, a safety factor of 2 indicates that the component can handle loads up to 2 times the simulated loads, and so on.

After the analysis, it is observed that the swing-arm reaches the lowest safety factor of 2.77 when it is being subjected to loads generated while navigating left turns. This minimum safety factor of 2.77 is still greater than the targeted safety factor of 2 set for the material Al 6061. The aforementioned statements are substantiated by the illustration given in Figure 10.

It is also observed that the swing-arm experiences a maximum deflection of 0.63 mm when it is being subjected to loads generated while navigating left turns. This maximum deflection of 0.63 mm is still
lower than the allowable deflection of 5.67 mm beyond which the component would fail. Figure 8 substantiates the above statements by providing the illustration.

![Figure 8: Maximum Deflection observed.](image)

5. CONCLUSION
This work studied the behavior of the single-sided swing-arm generated from the simulated aluminum alloys Al 6061 and Al 7075. The Generative Design Study and the Simulation for this study were carried out in AUTODESK Fusion 360. The mechanical properties of both the swing-arms were compared and it was decided to proceed with the analysis on Al 6061. After the analysis was carried out with Al 6061, the following was observed. Maximum Von Mises stress developed was 99.1 MPa. The minimum safety factor reached by the swing-arm was 2.77. The maximum deflection experienced was 0.63. These values were observed under the conditions that simulate a bike navigating a left turn. The volume and the mass of the swing-arm were found to be around 1.06 mm³ and 2.9 kg respectively.

The inference from the present work and the literature proves the superiority of Al 7075 over steels and considering the results from the analysis, it could be concluded that Al 6061 is a superior material than Al 7075 and steel for the fabrication of the single-sided swing-arm for intended gains from the process of light-weighting.

6. REFERENCES

[1] Wenlong S, Xiaokai C and Lu W 2016 Analysis of energy saving and emission reduction of vehicles using lightweight materials” *Energy Procedia* 889-893
[2] Cowell A 2018 Looking inside the heart of our championship winning car *Daimler Magazine*
[3] Patil K, Rajpurohit G, Magade R and Shirphule A 2019 Design and analysis of single-sided swing-arm for modified bike *Int. Res. J. of Eng. Technol.* 06 876-879
[4] Powar A, Joshi H, Khuley S, and Yesane D P 2016 Analysis and topological optimization of motorcycle swing-arm, *Int. J. of Curr Eng. Technol.* 270-274
[5] Satyanarayana K, Narendra M, Pavan Sai E, Sri Harsha, Babu G and Rao M 2020 Modelling and analysis of double sided monoshock swing-arm *JCT* 08 510-519
[6] Schaller B 1996 Experimental validation of finite element analysis software applied to the design of a motorcycle swing-arm (Embry-Riddle Aeronautical University - Daytona Beach)
[7] Cossalter V 2006 Motorcycle dynamics, Second English Edition
[8] Abdullah S H, Ahmed M and Rahman W A 2018 Design of racing motorcycle swing-arm with shape optimisation *Int. J. Sci. Res. & Dev* **06** 179 - 183
[9] Chengzhi Han 2020 *J. Phys.: Conf. Ser.* **1676** 012085
[10] Rosenthal S, Maaß F, Kamaliev M et al. 2020 Lightweight in automotive components by forming technology. *Automot. Innov.* **3**, 195–209