STRUCTURAL OPTIMIZATION OF DHIL ACTUATOR USING TOPOLOGY OPTIMIZATION METHOD

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BACHELOR OF MECHANICAL ENGINEERING TECHNOLOGY (AUTOMOTIVE TECHNOLOGY) WITH HONOURS

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I hereby declare that I have checked this thesis and, in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology (Automotive Technology) with Honours.

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Supervisor Name : Dr. Ts. Muhammad Zaidan bin Abdul Manaf

Date : 9 December 2024

DEDICATION

I owe this success to my parents, Abu Bakar bin Din and Rosnani binti Ishak, as well as to my professional supervisor, Dr. Ts. Muhammad Zaidan bin Abdul Manaf and my incredible friends. Without your support, love, and unshakable faith in me, I would not have accomplished this goal. Your presence in my life has made a huge difference, and I will always be appreciative of your unflagging encouragement and support. This accomplishment is both yours and mine. I appreciate you being an important part of my path.

ABSTRACT

This thesis focuses on the structural optimization of DHIL actuators using topology method. Structural optimization aims to enhance the performance and efficiency of structures by refining the shapes and materials. The primary goal is to determine the best possible configuration that minimizes the objective function and satisfies a set of constraints. This study employs an evolutionary structural optimization method, improving the solution quality by avoiding potential kinematic instabilities and including local error estimators. The research involves a detailed analysis of various types of structural optimization, including topology optimization, which is particularly emphasized. The topology optimization technique used in this study intelligently distributes material within a design domain to achieve optimal structural performance under specified load conditions and constraints. Applications of this optimization method span across industries such as automotive, aerospace, and civil engineering. This thesis presents the design, analysis, and optimization processes, culminating in a structurally optimized DHIL actuator model that demonstrates significant performance improvements and material efficiency.

ABSTRAK

Tesis ini memfokuskan kepada pengoptimuman struktur penggerak DHIL menggunakan kaedah topologi. Pengoptimuman struktur bertujuan untuk meningkatkan prestasi dan kecekapan struktur dengan memperhalusi bentuk dan bahan. Matlamat utama adalah untuk menentukan konfigurasi terbaik yang meminimumkan fungsi objektif dan memenuhi satu set kekangan. Kajian ini menggunakan kaedah pengoptimuman struktur evolusi, meningkatkan kualiti penyelesaian dengan mengelakkan ketidakstabilan kinematik yang berpotensi dan termasuk penganggar ralat tempatan. Penyelidikan ini melibatkan analisis terperinci tentang pelbagai jenis pengoptimuman struktur, termasuk pengoptimuman topologi, yang amat ditekankan. Teknik pengoptimuman topologi yang digunakan dalam kajian ini secara bijak mengagihkan bahan dalam domain reka bentuk untuk mencapai prestasi struktur yang optimum di bawah keadaan beban dan kekangan tertentu. Aplikasi kaedah pengoptimuman ini merentas industri seperti automotif, aeroangkasa dan kejuruteraan awam. Tesis ini membentangkan reka bentuk, analisis dan proses pengoptimuman, yang memuncak dalam model penggerak DHIL yang dioptimumkan secara struktur yang menunjukkan peningkatan prestasi yang ketara dan kecekapan bahan.

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LIST OF SYMBOLS AND ABBREVIATIONS

DHIL	-	Dynamic Hitch Lift
TO	-	Topology Optimization
FEA	-	Finite Element Analysis
NVH	-	Noise, Vibration and Harshness
ABS	-	Anti Breaking System
CFD	-	Computational Fluid Dynamic
ECU	-	Electronic Control Unit
UAV	-	Unmanned Ariel Vehicle
MKS	-	Meter, Kilogram. Meseener
FOS	-	Factor of Safety

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CHAPTER 1

INTRODUCTION

1.1 Research Overview

An optimization method is a systematic approach used to find the best solution from a set of feasible alternatives. It involves maximizing or minimizing a specific objective function while satisfying certain constraints. (Anders Hansson and Martin Andersen, 2023). Optimization methods are applied in various fields such as chemistry, geophysics, and resource allocation. In chemistry, optimization is used to determine reaction rate constants that best match experimental or detailed mechanism data. (Aleksander D. Zakharov, Roman Fursenko and Sergey Minaev, 2022). Geophysical exploration utilizes optimization techniques like Genetic Algorithms and Simulated Annealing to interpret seismic and well log data effectively. (Maurya S.P, Singh N.P, Singh K.H, 2020). Additionally, optimization methods involve complex calculations and evaluations to select the most optimal solution based on predefined conditions (Lynde Clément, 2020). The evolution of mathematical tools and digital computers has significantly enhanced the efficiency of optimization processes across disciplines (Antonio Frangioni., Laura Galli, 2020).

1.2 Problem Statement

Dynamic Hitch Lift (DHIL) actuators are essential in agricultural and construction machinery for precise lifting and positioning of heavy loads. However, current designs face significant limitations, such as excessive weight, inefficient material usage, and reduced structural performance. Over-engineering leads to higher energy consumption, increased operating costs, and greater wear and tear on machinery. Ensuring a high strength-to-weight ratio is critical to improving performance and durability under demanding conditions.

To address these issues, applying topology optimization can help achieve a more efficient material distribution, resulting in lighter, stronger, and more reliable actuators. This research focuses on redesigning DHIL actuators using advanced optimization techniques to enhance their performance, reduce material usage, and lower overall costs.

1.3 Research Objective

The main aim of this research is to develop a structurally optimized design for the DHIL actuator by applying structural optimization techniques such as, topology optimization. Specifically, the objectives are as follows:

1. Review the current design of Dynamic Hitch Lift (DHIL) actuator to identify key areas for improvement and optimization.
2. Perform structural analysis and topology optimization method to refine the structure of Dynamic Hitch Lift (DHIL) actuator, to improve mechanical strength while minimizing weight.

1.4 Research Scope

The scope of this research are as follows:

From Objectives 1:

- Study factors such as materials used, geometry, and manufacturing processes to understand their impact on performance.
- Identify specific areas where the current design may fall short in terms of mechanical strength or durability.
- Evaluating how well the actuators meet performance criteria such as mechanical strength or durability.

From Objectives 2:

- Run static analysis to examine stress distribution, deformation, and stability.
- Perform topology optimization to refine the design to meet specific objectives, such as minimizing weight, improving structural performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review is a key part of this research, providing an overview of previous studies on the structural optimization of Dynamic Hitch Lift (DHIL) actuators using topology optimization. DHIL actuators are crucial for improving load distribution, stability, and handling in heavy-duty machinery and vehicles. Unlike passive systems, DHIL actuators dynamically adjust suspension to enhance safety and comfort under varying conditions.

Current DHIL designs often suffer from excess weight and inefficiency. Structural optimization, particularly using topology optimization, offers a solution by minimizing material usage while maintaining strength, improving performance, durability, and sustainability. This chapter reviews existing research and identifies gaps, forming the basis for advancing the design and optimization of DHIL actuators.

2.2 Introduction To Dynamic Hitch Lift (DHIL) Actuator

Dynamic Hitch Lift (DHIL) actuators are key components in enhancing the performance of vehicles involved in towing and hauling. They are designed to dynamically adjust the vehicle’s suspension system, optimizing stability, handling, and load distribution in response to changing conditions. Figure 2.1 shows DHIL on a towing truck.

Figure 2.1 DHIL on towing truck

By managing the elevation of the hitch assembly, DHIL actuators effectively counteract the effects of dynamic loads and road disturbances, improving safety and comfort during operation. Unlike traditional systems, DHIL actuators provide real-time adjustments, ensuring a more balanced and controlled vehicle-trailer interaction across diverse operating scenarios.

2.3 Structural Optimization

Structural optimization is the process of finding the most efficient design for a structure, considering factors such as weight, cost, and performance. (Prager ,1970). It involves creating structures that sustain loads with minimal material use while maintaining strength and durability. The goal is to achieve objectives such as minimum weight, maximum stiffness, resistance to instability

Structural optimization is crucial for improving efficiency and performance in engineering projects. It minimizes weight and material usage, which directly reduces costs. Additionally, it enhances structural performance by increasing stiffness and stability. This leads to more reliable and cost-effective designs. Structural optimization contributes to more sustainable engineering practices by optimizing material use and reducing waste. It makes manufacturing processes more eco-friendly by lowering the environmental impact and promoting resource efficiency. Structural optimization, especially through cloud-native simulation, enables the creation of complex and efficient designs that would be unattainable with traditional methods. (Richard Szoke-Schuller, 2024).

2.4 Types of Structural Optimization

Structural optimization includes several methods designed to improve the effectiveness and efficiency of structures. These methods vary but serve the common goal of enhancing structural performance. There are various types of structural optimization approaches, including Topology Optimization, Shape Optimization and Sizing Optimization.

2.4.1 Topology Optimization

Topology Optimization (TO) is a process that optimizes material layout and structure within a given 3D geometrical design space for a defined set of rules set by the designer. The goal is to maximize part performance by mathematically modelling and optimizing for factors such as external forces, load conditions, boundary conditions, constraints, and material properties within the design envelope. (Bends e, M.P., and Sigmund, O. 2003)

Topology optimization has been used by mechanical and civil engineers for many years, for example in order to minimize the amount of used material and the strain energy of structures while maintaining their mechanical strength (Bendsoe et al., 2003)

Topology optimization is typically conducted at the end of the design phase when reducing the product's weight becomes a priority. Figure 2.2 shows the topology optimization steps of simple bracket.

The process begins with creating the initial part geometry or design space. The user then defines preserved areas, such as mounting points and regions around critical features like screw heads or bearing bores. Next, external loads, constraints, and material properties are specified. Once these inputs are set, the user generates and refines the mesh, a crucial step in topology optimization to ensure accurate analysis.

The optimization objective is then selected, such as minimizing weight or maximizing stiffness. After that, the software runs the topology optimization, analyzes the design, and highlights critical areas to retain. The user evaluates the results and adjusts levels to refine the outcome. Finally, the optimized geometry is exported and edited to ensure it is suitable for manufacturing, followed by a final analysis to verify the part's performance.

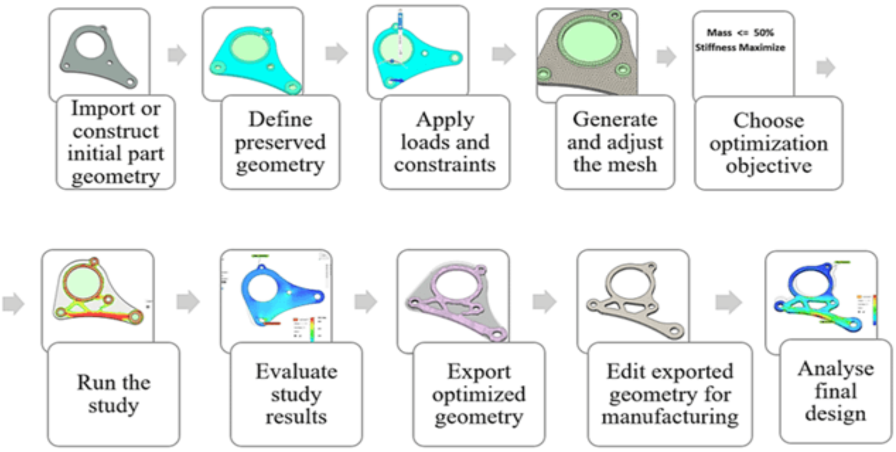


Figure 2.2 Topology Optimization Steps (researchgate.net)

Like any other design tool or product design process, topology optimization has advantages and disadvantages. Topology optimization has several advantages. It helps create efficient designs by reducing unnecessary material, resulting in lighter and more cost-effective products with a better strength-to-weight ratio. This saves on production, transport, and packaging costs while promoting sustainability. Topology optimization also speeds up the design process by quickly testing different options and reducing failure risks. When used with 3D printing, it allows for complex shapes without extra cost.

However, topology optimization has some disadvantages. It works better with additive manufacturing (AM) than traditional methods, which can be slower and more wasteful. Optimized designs may be costly if advanced techniques like 3D printing or injection molding are required. In some cases, reducing material may lower strength if inputs are not properly set. Since topology optimization is still new to many industries, it needs time for wider adoption and understanding. (Bends e, M.P., and Sigmund, O. 2003)

2.4.2 Size Optimization

Size optimization deals to find the optimum cross-sectional areas of the elements, shape optimization works by shifting the nodal positions (Kaveh & Talatahari, 2009). Size optimization is the process of determining the best dimensions, such as thickness, length, or volume, of a design to meet performance requirements while minimizing material use or cost. Unlike topology optimization, which alters the shape or structure of a part, size optimization focuses on adjusting the dimensions of an existing design. Its goal is to enhance factors like strength, stiffness, weight, and manufacturing efficiency. Size optimization is widely applied in engineering and product design to improve material efficiency and reduce production costs while ensuring the design meets specific performance goals (Xie & Steven, 1993).

Using size optimization method in spot weld design of automotive body structures, different combinations of static and/or dynamic loading scenarios can be considered simultaneously, related to the bending and torsional stiffnesses, the Noise, Vibration and Harshness (NVH) performance and the structural crashworthiness. To reduce the computational cost, surrogate models based on finite element analyses (FEA) results are often used to predict structural performances in the optimization procedure. (Lei Yan, 2021)

A comparison of size optimization, shape optimization, and topology optimization based on a structural mechanics problem is shown in Figure 2.3

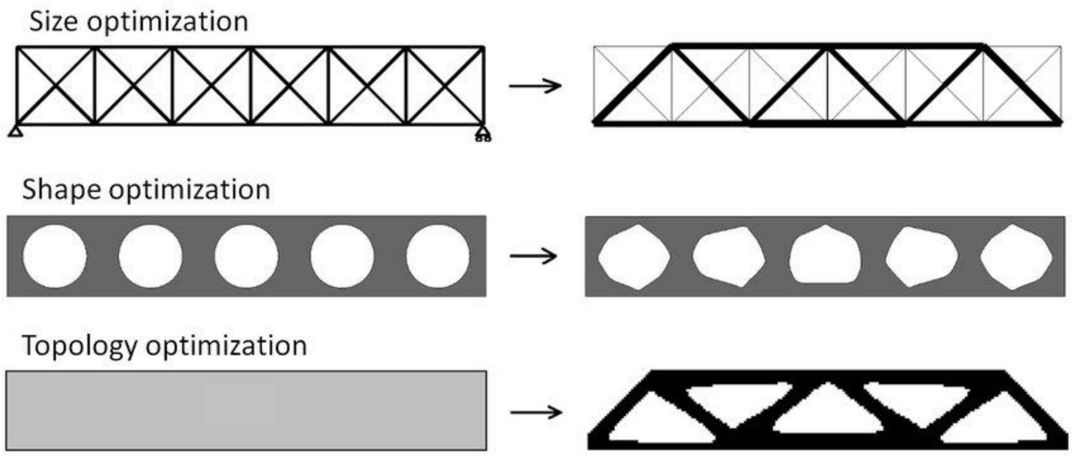


Figure 2.3 Comparison of size optimization, shape optimization, and topology optimization (Bendsoe and Sigmund, 2003).

Sizing optimization is one of the most common types of structural optimization applied in industry. This is mainly due to the fact that sizing optimization problems are defined, solved and post processed with relatively small effort and only few manufacturing constraints are required for obtaining industrial feasible solutions. (N. Gerzen, P. M. Clausen & C. B. W. Pedersen, 2016)

2.4.3 Shape Optimization

Shape optimization is part of the field of optimal control theory. The typical problem is to find the shape which is optimal in that it minimizes a certain cost functional while satisfying given constraints. In many cases, the functional being solved depends on the solution of a given partial differential equation defined on the variable domain. (Allaire, G. 2002).

Shape optimization is a complex and interdisciplinary field that involves finding the optimal shape of a component to minimize a cost function, often related to mass, stress, or natural frequencies (Haslinger, 1995; Hsu, 1994).

Efficient modeling is crucial in shape optimal design, with a focus on structural analysis, mathematical programming, and computer-aided geometric design (Bletzinger, 1991). The practical application of shape optimization involves the optimal distribution of mass, often achieved through the introduction of foam-like materials with variable density (Mlejnek, 1993). Figure 2.4 shows the step of shape optimization from initial design to morphing. Then the optimization process occurs and shows the result of optimized design.

Shape optimization involves finding the optimal shape or contour for an engineering component or product within specific constraints by modifying a set of predefined boundaries. In product design, shape optimization is highly beneficial. It enhances the understanding of the design space and offers valuable guidance to design teams, enabling the creation of products with improved performance and lower risks. Additionally, shape optimization reduces the time required to transition a product from the design phase to user deployment. It also helps cut costs by preventing costly last-minute modifications.

Shape optimization plays a vital role throughout the design cycle, both in the early and advanced phases. During the initial phase, it allows for the exploration of new ideas and possibilities. In the later stages of product design, its flexibility and quick adaptability facilitate rapid adjustments to design changes. These advantages lead to the development of products with superior performance and provide a broader range of design variants to choose from. Moreover, shape optimization significantly contributes to expanding the knowledge base, supporting high-quality decision-making. (Ravindra Krishnamurthy, 2019)

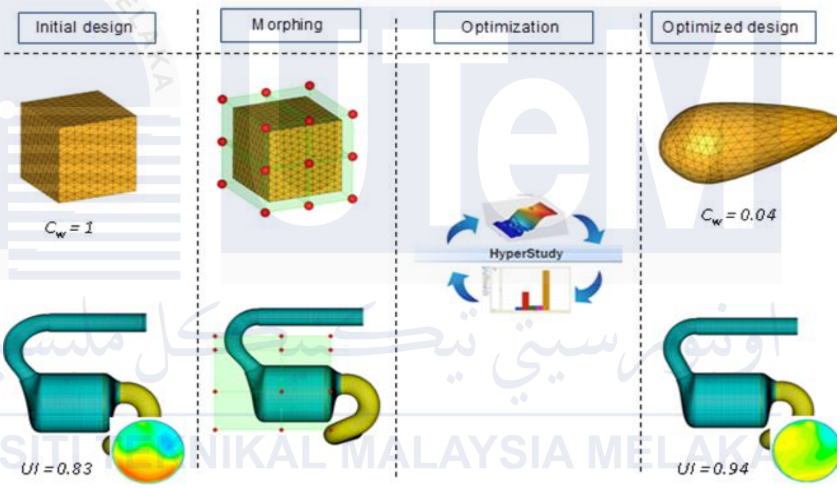


Figure 2.4 Steps of Shape Optimization

Figure 2.4 shows the step of shape optimization from initial design to morphing. Then the optimization process occurs and shows the result of optimized design. Shape optimization involves several key steps to find the best design for a product or component. First, the goals and constraints of the optimization are defined, such as reducing weight, improving strength, or meeting size limitations. Then, a mathematical model is created, including an objective function and constraints that represent the design’s performance and requirements. Next, an optimization method, like gradient-based techniques or genetic algorithms, is selected to modify the shape iteratively. Using tools like Finite Element Analysis (FEA), simulations are run to assess the design's performance after each modification. The process continues until the design converges and no further improvements can be made. Finally, the optimized design is validated through simulations and, if possible, physical testing. Any necessary adjustments are made, and the design is prepared for production.

2.5 Application of Optimization in Dynamic System

Optimization in dynamic systems involves finding the best possible solutions to improve the performance and efficiency of systems that change over time. These systems, such as control systems, power grids, transportation networks, and even biological processes, require continuous adjustments to adapt to varying conditions. By applying optimization techniques, it is possible to make decisions that minimize costs, maximize efficiency, and ensure stability. This approach is widely used across many industries to enhance operations, reduce waste, and achieve better outcomes in systems that are constantly evolving.

2.5.1 Optimization in Automotive Engineering

In automotive engineering, optimization is used to enhance suspension systems, powertrains, and active safety systems. By dynamically adjusting suspension parameters, optimized suspension systems improve ride comfort and handling. Powertrains in hybrid and electric vehicles benefit from optimized energy management strategies and component design, leading to greater efficiency. Additionally, control algorithms in active safety systems, such as anti-lock braking systems (ABS) and electronic stability control (ESC), are optimized for better performance. Figure 2.5 shows the automotive chassis topology optimization.

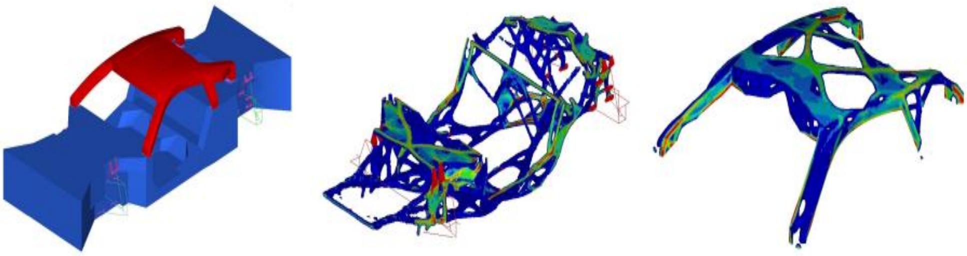


Figure 2.5 Automotive chassis topology optimization (Marco Cavazutti, 2012)

Topology optimization has been applied to the design of an automotive chassis. The objective of the optimization is still the weight reduction while the performance requirements regard handling and safety standards, global bending and torsional stiffnesses, crashworthiness in the case of front crash, modal analysis, local stiffness of the suspension, engine, and gearbox joints. The initial design space is given by the provisional vehicle overall dimensions. The results for the chassis and the roof are shown in Figure 2.5 (Marco Cavazutti, 2012)

2.5.2 Optimization in Aerospace Engineering

In aerospace engineering, flight control systems are optimized to improve aircraft stability and maneuverability under various flight conditions. Structural components are designed using topology and shape optimization to reduce weight while maintaining dynamic performance under different loads. Propulsion systems, including jet engines and rocket motors, are optimized to enhance efficiency and thrust-to-weight ratios. Figure 2.6 shows topology optimization in aircraft and aerospace structures design.

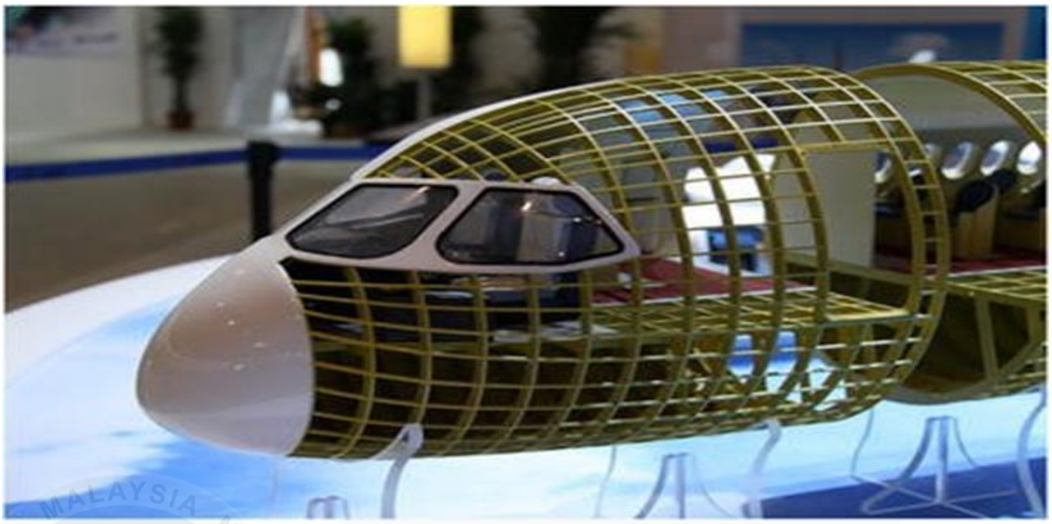


Figure 2.6 Aerospace Structures Design (Ji Hongzu, 2015)

In the context of civil aircraft wing design, a multi-objective, multi-disciplinary approach has been shown to be essential, with the use of computational tools such as computational fluid dynamics (CFD) and stochastic process response surface models (Keane, 2007). The integration of optimization into the process of engineering design is crucial for improving and optimizing technical designs, structural assemblies, and components (Eschenauer, 1993).

2.5.3 Optimization in Mechanical Engineering

Mechanical systems, such as those in robotics and machinery, also benefit from optimization. Vibration control is improved by optimizing the design of dampers and absorbers, which reduces vibrations and extends the lifespan of machinery. Robotics systems are optimized for better precision, speed, and adaptability in dynamic environments. Figure 2.7 shows the topology optimization of a lever.

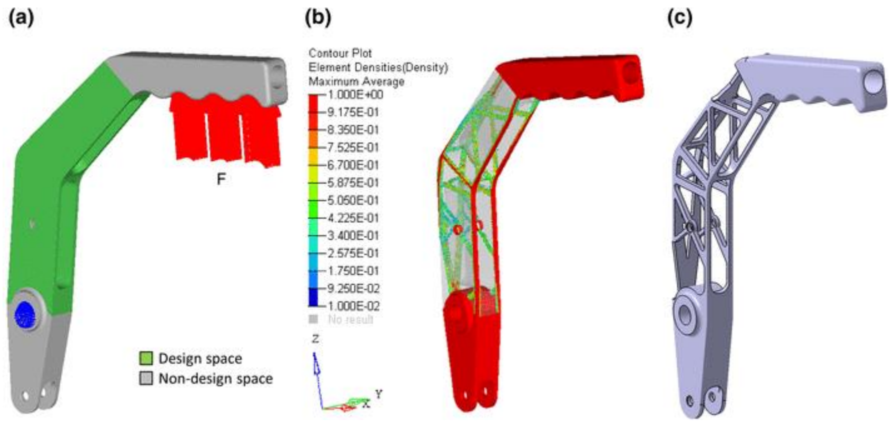


Figure 2.7 Topology optimization of a lever (Laura Berrocal, 2019)

2.5.4 Optimization in Civil Engineering

Civil engineering applications include optimizing building and bridge designs for better seismic response, ensuring safety and structural integrity during earthquakes. Wind-resistant structures are also optimized to withstand dynamic wind loads by refining shape and material distribution.

The purpose of optimization in civil engineering is design of a structure to achieve the minimum weight and construction cost of the structure in addition to satisfaction of the technical aspects of the problem. (S. Mohtaram, 1970). The use of optimization in civil engineering is expanding, with a focus on different algorithms and their applications (Zaheer 2023.

2.6 Optimization Space

The concept of the optimization space is central to the process of structural optimization, particularly in engineering fields like automotive, aerospace, and civil engineering. The optimization space is essentially a subset of the design space where modifications can be made to a structure's material distribution or geometry to achieve optimal performance. This performance can be defined in terms of minimizing weight, maximizing strength, enhancing stiffness, or reducing costs, among other objectives. The optimization space comprises design regions and non-design regions, each serving a distinct purpose in the optimization process.

2.6.1 Design Space

The design region is the portion of the structure where material can be added, removed, or redistributed to meet specific objectives. This is the primary area where optimization algorithms operate to improve performance characteristics, such as minimizing weight while maintaining structural integrity. The design region is typically defined based on engineering requirements, and engineers use computational models to identify areas where changes in material distribution can lead to significant performance gains. A design space is the initial geometry that forms the boundary of the optimized shape. It is typically a simplified representation of the existing part, with holes and pockets removed. Increasing the material available in the design space will yield a more optimized result. (Altair Engineering) Figure 2.8 shows the design space part in reddish brown.

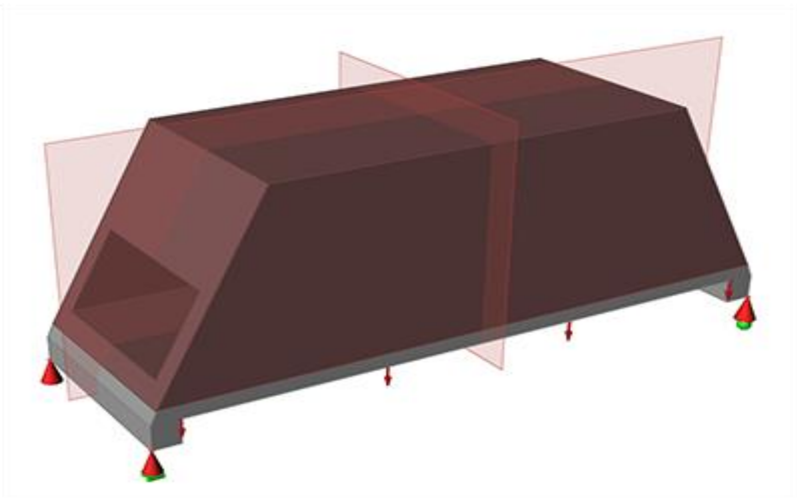


Figure 2.8 Design Space (Altair Inspire)

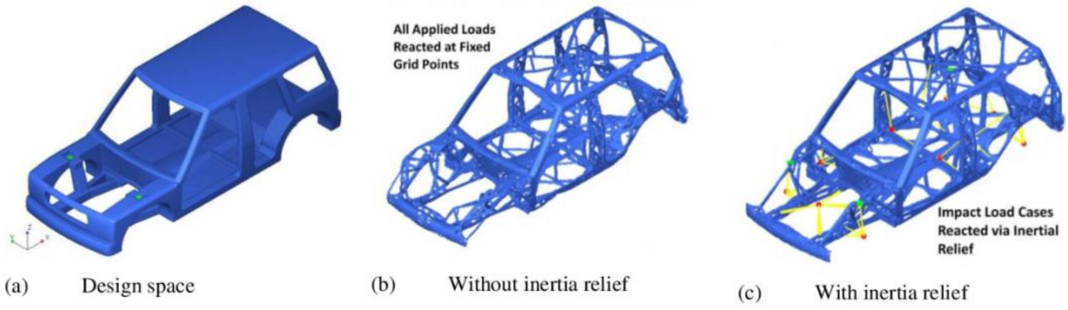


Figure 2.9 Configuration of the (a) design space, (b) optimized body structure without inertia relief, and (c) optimized body structure with inertia relief (Quinn, 2010)

In car chassis design, the design region includes areas where material can be reduced to lower the vehicle's weight without compromising safety, as shown in Figure 2.9. Optimization algorithms adjust the material or shape in these regions and evaluate performance using simulations like finite element analysis (FEA). In civil engineering, optimization is used to improve building and bridge designs for better earthquake resistance, ensuring safety and stability. Similarly, wind-resistant structures are optimized by refining their shape and material distribution to withstand strong winds.

2.6.2 Non-Design Space

In structural optimization, non-design regions are areas where modifications are restricted to maintain the structure's functional integrity. These typically include load-bearing sections, interfaces with other components, or areas subject to strict design constraints. Non-design regions serve as fixed boundaries during the optimization process, ensuring that essential structural features remain unchanged. Figure 2.10 shows the classification of the non-design area and the topology optimization domain

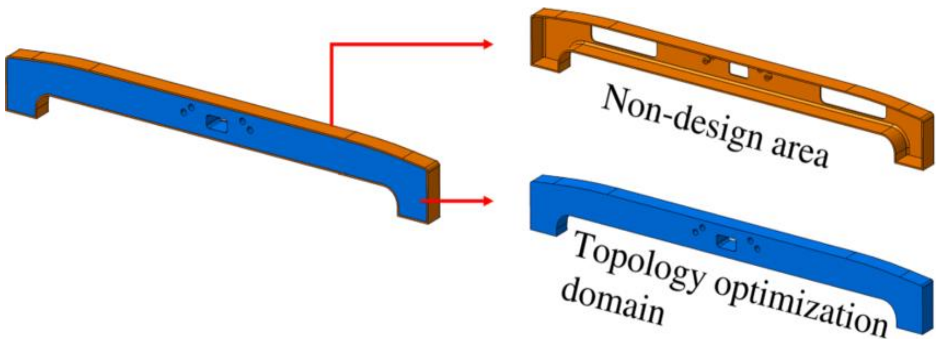


Figure 2.10 Non design area and topology domain (S.W. Park, 2018)

Figure 2.11 Non-Design Space in grey color (Altair Inspire)

For instance, in an aircraft wing, the attachment points to the fuselage are considered non-design regions. Altering these critical areas could compromise the overall safety and functionality of the aircraft. By keeping these regions constant, engineers can focus on optimizing other parts of the design without affecting crucial components. Figure 2.11 shows the design space part in grey color.

2.7 Design and Functionality of DHIL Actuator

Numerous studies have examined the design and functionality of DHIL actuators. These actuators are engineered to maintain vehicle equilibrium under varying operating conditions by dynamically adjusting suspension parameters. Traditional passive suspension systems often fail to adapt to dynamic load changes and road conditions, leading to decreased vehicle control and increased wear on components. Research indicates that DHIL actuators can address these issues by actively managing suspension adjustments in real-time. For instance, Smith et al. (2020) demonstrated that DHIL actuators significantly enhance vehicle stability and load distribution during towing operations, resulting in improved safety and comfort. Figure 2.12 shows the slide in wheel lift.

Figure 2.12 Slide in wheel lift (Minuteman1.com)

The Dynamic Hitch Lift Controller (DHIL) actuator is a critical component in agricultural machinery, designed to control the lifting and positioning of mounted implements on a tractor. Its primary purpose is to ensure smooth, precise, and responsive control over the hitch mechanism, enabling better traction, load distribution, and overall operational efficiency during various farming tasks. The design of the DHIL actuator integrates mechanical, hydraulic, and electronic elements to provide robust performance under dynamic field conditions.

2.7.1 Design and of DHIL Actuator

The DHIL actuator consists of several key elements that work together to deliver optimal hitch control. The central component is the hydraulic cylinder, which generates the force required to lift or lower the attached implement. The cylinder is driven by pressurized hydraulic fluid supplied by the tractor's hydraulic system. The actuator design ensures that the motion is not only powerful but also smooth, allowing for precise adjustments based on field conditions. Figure 2.13 shows the part of tractor three-point hitch control for independent arm.

Figure 2.13 Tractor Three Point Hitch (Yogesh M. Chukwad, 2024)

Position monitoring is achieved through the integration of position sensors, which continuously track the height and angle of the hitch relative to the tractor. These sensors provide real-time feedback to the electronic control unit, ensuring precise control over implement positioning. Additionally, load sensors play a crucial role in detecting the forces exerted on the hitch by the attached implement. This data helps in dynamically adjusting the hydraulic pressure, ensuring that the load is distributed evenly and preventing excessive strain on the tractor or the implement.

The Electronic Control Unit (ECU) forms the brain of the DHIL actuator system. It processes input from the position and load sensors, along with other parameters such as ground speed and engine load, to dynamically control the actuator's movement. The ECU uses advanced control algorithms to ensure that the hitch remains stable and performs optimally, even on uneven or slippery terrain. Figure 2.14 shows the electric hitch lift on a truck.

Figure 2.14 Electric hitch Lift

To regulate the hydraulic fluid flow, the DHIL actuator includes hydraulic control valves. These valves precisely control the amount of hydraulic fluid entering or exiting the cylinder, determining the speed and force of the actuator's motion. The valves respond to signals from the ECU, ensuring that the hitch movements are accurate and responsive to changes in load or terrain.

2.7.2 Functionality and of DHIL Actuator

The DHIL actuator operates by dynamically controlling the position of the hitch based on feedback from its sensors. When an operator adjusts the hitch height, the ECU processes this input along with sensor data to determine the required hydraulic pressure. The hydraulic fluid is then directed to the cylinder through the control valves, causing the hitch to lift or lower accordingly.

One of the key features of the DHIL actuator is its ability to maintain a constant depth of the implement during operations such as plowing or tilling. As the tractor moves across the field, varying soil conditions may cause the implement to sink too deep or rise too high. The DHIL actuator continuously adjusts the hitch position in real time, ensuring that the implement maintains a consistent depth, improving field productivity and reducing operator fatigue.

The actuator also plays a crucial role in load control, ensuring that the tractor's rear wheels maintain proper contact with the ground for optimal traction. By adjusting the hitch dynamically in response to load changes, the DHIL actuator prevents wheel slippage, improving fuel efficiency and reducing wear on the tractor's tires.

2.7.3 Application of DHIL Actuator

The DHIL actuator is widely used in various farming operations, such as plowing, tilling, seeding, and harvesting. Its ability to precisely control the hitch position ensures consistent implement performance, leading to better crop yields and reduced soil compaction. Additionally, the DHIL actuator is essential in operations involving heavy loads, such as transporting large trailers or operating heavy-duty equipment. Its dynamic load control capabilities ensure that the tractor remains stable and safe under all operating conditions.

Moreover, the DHIL actuator's real-time adjustment capabilities make it highly useful in precision agriculture, where accurate implement positioning is critical for tasks such as planting and fertilizing. By integrating advanced control algorithms with sensor feedback, the DHIL actuator ensures that these tasks are performed with high accuracy, reducing waste and improving resource efficiency.

2.7.4 Advantages of DHIL Actuator

The DHIL actuator offers several advantages in agricultural operations. Its dynamic control capability allows it to respond quickly to changes in load or terrain, ensuring consistent performance and safety. The integration of sensors and feedback mechanisms provides high precision, enabling accurate implement positioning and depth control. This not only improves operational efficiency but also reduces operator workload, as the actuator handles most of the fine adjustments automatically.

Another key advantage is load distribution optimization. By adjusting the hitch position to maintain proper traction, the DHIL actuator reduces wheel slippage and improves fuel efficiency. This not only extends the life of the tractor's tires but also reduces overall operational costs. Furthermore, the DHIL actuator's robust design ensures long-term reliability in demanding field conditions, making it a valuable component in modern agricultural machinery.

Finally, the DHIL actuator supports automation and smart farming, as it can be integrated with advanced tractor systems for automated guidance and precision farming. This opens the door to future innovations, where tractors equipped with DHIL actuators can operate autonomously, performing tasks with minimal human intervention.

2.8 Performance Improvement and Techniques

The Dynamic Hitch Lift Controller system improves towing performance by automating the hitching and lifting process. It uses electric or hydraulic actuators for smooth, precise movements, reducing manual effort and human error. Real-time sensors monitor and adjust the hitch's position to ensure proper alignment and balance, preventing tipping. The system includes an easy-to-use interface that allows operators to control it easily, while adaptive algorithms optimize performance based on conditions like weight and terrain.

For safety, the system integrates active suspension and vibration damping to absorb shocks and reduce wear. It's built with durable materials to last longer in tough environments. The system is energy-efficient, using low-power components and sometimes incorporating energy recovery to save power. Self-diagnostics and predictive maintenance help identify issues early and reduce repairs.

Optimization algorithms ensure the system adapts to changing conditions, and integration with the vehicle's suspension system enhances stability. Overall, the Dynamic Hitch Lift improves towing safety, efficiency, and reliability.

2.9 Application of Optimization Techniques

Optimization techniques are essential for improving the efficiency, safety, and performance of Dynamic Hitch Lift Control systems. These techniques help control the lift's motion by determining the most efficient path, speed, and force, reducing unnecessary movements and energy use. They also ensure proper load distribution by balancing the weight and adjusting for any shifts, preventing instability. Optimization is used to enhance energy efficiency by minimizing power consumption and using recovered energy. Predictive algorithms monitor system performance, helping with maintenance by detecting potential issues before they cause failures. Additionally, optimization allows the system to adapt to different conditions, like trailer weight or terrain, ensuring smooth operation. It can also be integrated with the vehicle's suspension for better stability while towing. Overall, optimization ensures that the Dynamic Hitch Lift Control operates reliably, safely, and cost-effectively.

2.10 Challenges and Future Directions

Dynamic Hitch Lift Control systems face several challenges, such as managing varying loads, reducing energy consumption, ensuring sensor accuracy, and integrating with vehicle control systems. The cost of high-performance materials and maintaining system durability under heavy use are also significant concerns. To address these issues, the future of Dynamic Hitch Lift Control systems looks promising with advancements in artificial intelligence (AI) and machine learning, which could optimize performance in real-time. Energy harvesting technologies could reduce reliance on external power, and smarter materials may improve both durability and efficiency. Improved sensors, wireless integration, and the potential for autonomous hitching could make these systems more reliable and easier to use. As the technology advances, production costs may decrease, making Dynamic Hitch Lift Control more accessible and cost-effective for a wider range of applications.

CHAPTER 3

REVIEW AND ANALYSIS OF CURRENT DHIL ACTUATOR

3.1 Introduction

This chapter reviews and analyzes the current design of the Dynamic Hitch Lift Controller (DHIL) actuator. The goal is to examine the actuator's structure and performance to identify areas that can be improved through optimization.

The chapter starts with a baseline study of the current DHIL actuator, looking at its design, materials, and performance. It highlights any limitations or inefficiencies, focusing on where structural improvements can enhance performance, such as reducing weight, increasing strength, or using materials more efficiently.

Next, the parameters of the old and initial designs are discussed. This includes details about the current actuator's size, materials, and load capacity, followed by a comparison with the initial design. This comparison helps identify key differences and areas where improvements can be made.

The chapter then explains the steps for applying structural analysis to both the old and initial designs. It covers setting up the optimization problem, selecting key parameters, and defining the constraints needed for the actuator to work effectively. The optimization process is described in simple steps.

Finally, the structural analysis results for both the current and initial designs are presented. These results are compared, showing the effectiveness of the current design and potential improvements from optimization.

3.2 Research Flowchart

One of the suggestions for optimizing the procedure throughout this project or the task was to compile a flowchart that would serve as a reference point. The benefits of taking this action included establishing an organized working structure as a component of the working environment, which increased the project's chances of success. The research flowchart that works as this project's working schedule can be seen in Figure 3.1. The flowchart includes a comprehensive description of all the project's procedures.

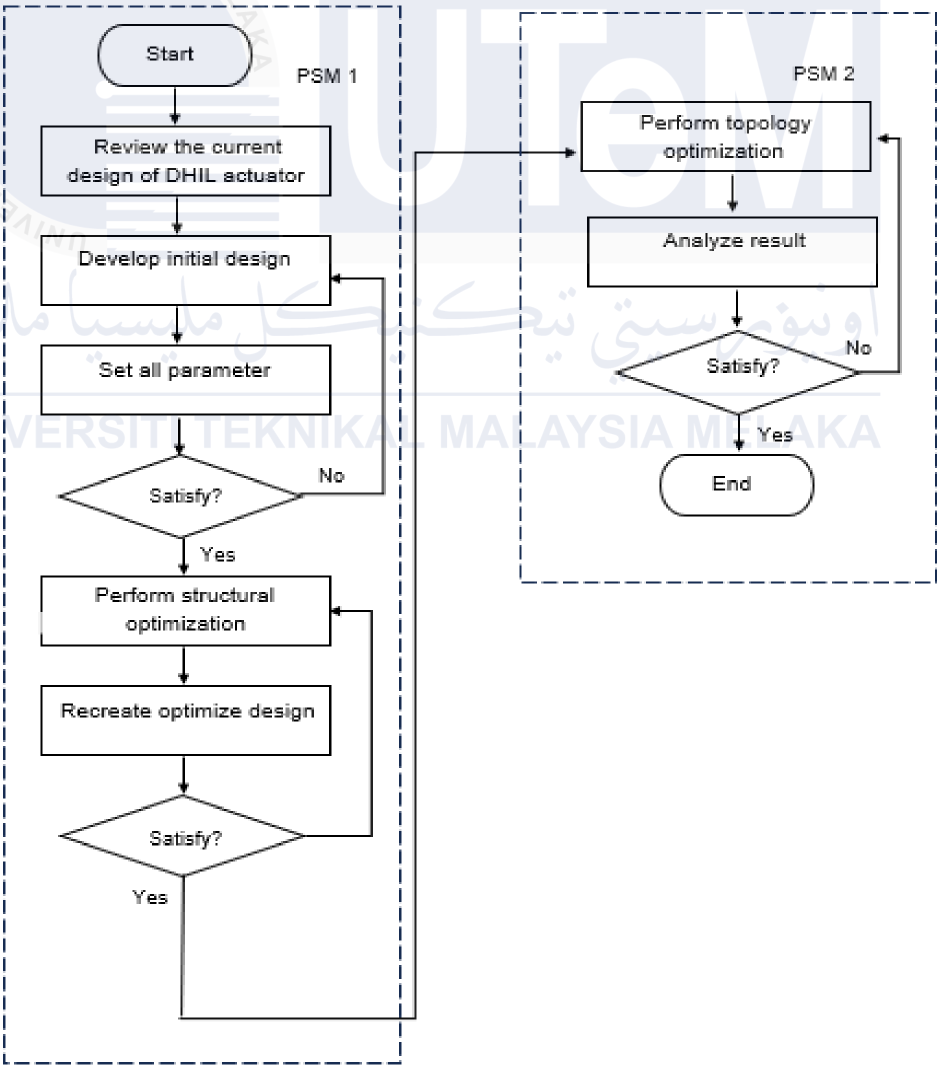


Figure 3.1 Research Flowchart

3.3 Baseline Study

The evolution of Dynamic Hitch Lift Controllers (DHIL) has been significantly influenced by advancements in both hydraulic and electronic control systems. Traditionally, DHIL actuators relied on hydraulic mechanisms for controlling and adjusting the hitch, often providing limited precision and responsiveness. However, with the introduction of electronic control mechanisms, the performance and flexibility of these systems have improved, enabling more precise and adaptable control over the actuator's movements.

One key technique that has contributed to the development of DHIL systems is dynamic inversion, a control strategy often employed in dynamic systems with complex interactions, such as Unmanned Aerial Vehicle (UAV) lateral control. Dynamic inversion works by compensating for dynamic coupling that occurs between different parts of a system, particularly when there is model mismatch between the expected and actual system behavior. This method effectively cancels out dynamic coupling, leading to improved stability and controllability of the system. While commonly applied in aerospace, this technique has shown promise in applications like DHIL actuators, where similar dynamic challenges in controlling suspension systems and load adjustments arise. By using dynamic inversion, DHIL systems can achieve smoother, more stable operations, especially when dealing with varying loads or road conditions.

DHIL actuators are crucial components in enhancing vehicle performance, particularly in towing and hauling scenarios. These actuators continuously adjust the vehicle's suspension system in real-time, optimizing factors such as stability, handling, and load distribution. This dynamic adjustment ensures that the vehicle maintains optimal balance and control, regardless of the load or external conditions. In particular, DHIL actuators contribute to reducing the risk of overloading, tipping, or uneven weight distribution, all of which can negatively impact both safety and efficiency.

Over the years, the performance of DHIL actuators has been improved through various innovations. Early systems relied on mechanical feedback loops, but modern designs use more sophisticated electromechanical actuators, often integrated with sensor systems to provide continuous feedback and adjustments. These actuators can dynamically sense the load conditions and terrain changes, adjusting the suspension to ensure the vehicle remains stable and well-balanced.

Additionally, the application of optimization techniques has played a key role in the evolution of DHIL actuators. Structural optimization methods, such as topology optimization, have been employed to design lighter, more efficient actuators without compromising strength or durability. These optimization techniques not only improve the actuator's performance but also contribute to its energy efficiency by minimizing material usage and reducing the power required for operation. Advances in computational tools and simulation techniques have made it possible to simulate and test actuator designs before physical implementation, allowing engineers to identify the most efficient designs. This section reviews previous studies on DHIL actuators, focusing on their design, performance, and the application of structural analysis.

3.4 Current Design of DHIL Actuator

In the DHIL actuator system, the lifting arm plays a crucial role in supporting and adjusting the load during towing. This arm is typically designed to be both strong and flexible, enabling it to dynamically adjust to different weight distributions and conditions. The arm's movement is controlled by the actuator, which uses advanced sensors and control strategies to ensure precise positioning. The system can adapt to changing loads, enhancing the vehicle's stability and handling while maintaining safety and operational efficiency during heavy-duty tasks. Figure 3.2 and 3.3 shows the current Dynamic Hitch Lift Controller and Dynamic Hitch Lift Controller on a Truck.

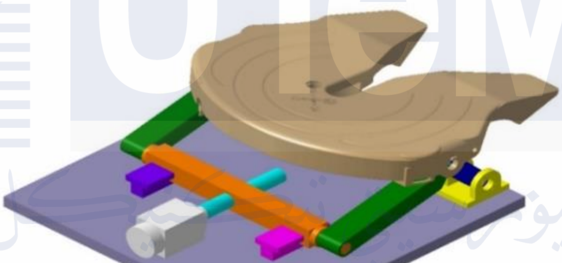


Figure 3.2 Dynamic Hitch Lift Controller (M.Z. Abdul Manaf, 2024)

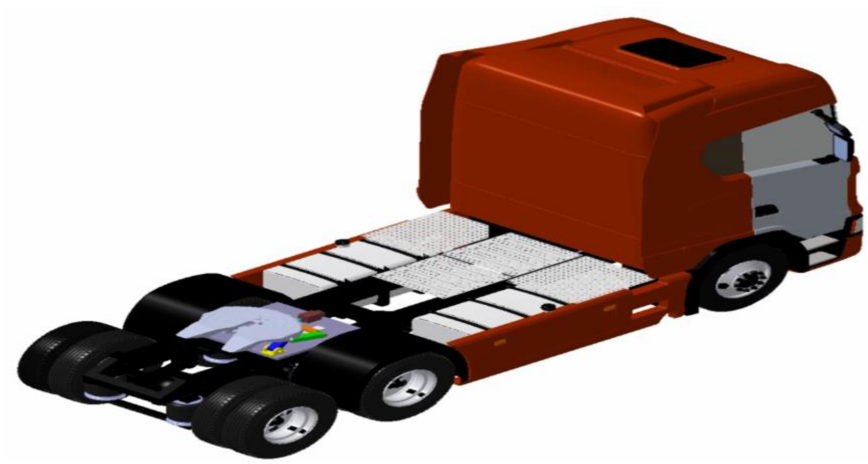


Figure 3.3 Dynamic Hitch Lift Controller on a Truck (M.Z. Abdul Manaf, 2024)

3.5 Parameters

The parameters of the DHIL actuator's arm play a crucial role in ensuring the system's functionality, safety, and overall performance. Key specifications such as the actuator's arm size, material properties, and load capacity directly influence its ability to handle dynamic loads while maintaining stability and control. All units are in mm.

3.5.1 Parameters of Original Design

The parameters of the DHIL actuator's arm are crucial in ensuring that the system can effectively handle dynamic loads and provide the necessary stability. Key factors such as the length, material strength, geometry, and range of motion must be carefully designed to ensure the arm can lift and support heavy loads while maintaining the required stability, and control during operation. These parameters directly impact the performance, safety, and efficiency of the actuator in real-world applications, ensuring that the system meets both functional and operational requirements. Figure 3.4 and 3.5 shows the original design of DHIL actuator's arm and the draft sketch of old design DHIL actuator's arm with its parameter. The material used is steel.

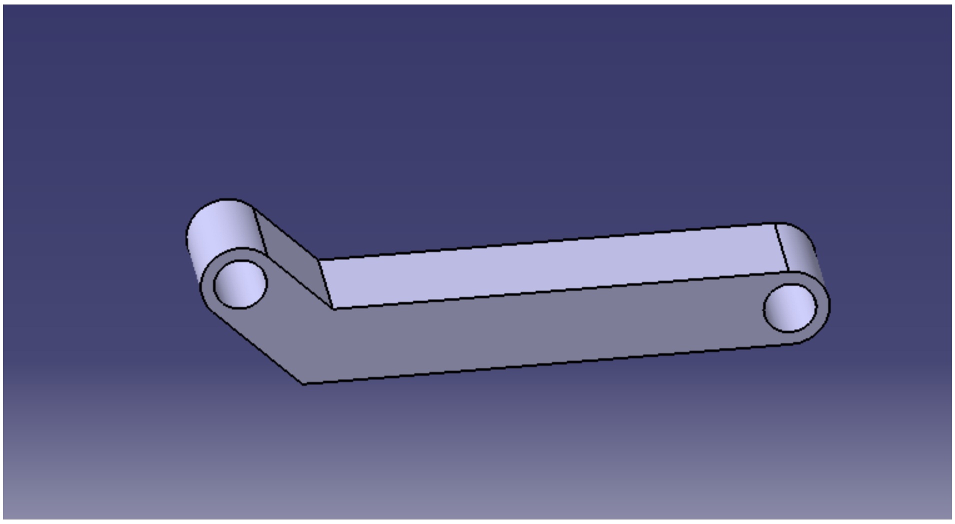


Figure 3.4 Original Design of DHIL actuator's arm

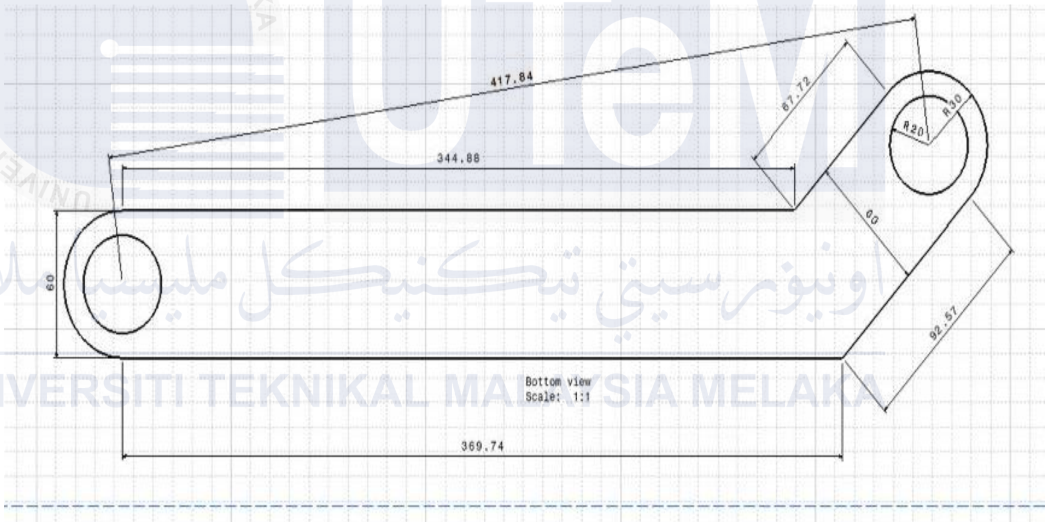


Figure 3.5 Draft sketch of original design DHIL actuator's arm with parameters

3.5.2 Parameter of Initial Design

The initial design of the arm of DHIL actuator serves as the starting point for the optimization process. This design is based on the functional requirements and constraints specific to the application of the actuator. The parameters of the initial DHIL actuator's arm have been confirmed. These adjustments aim to increase the arm's load-bearing capacity, durability, and efficiency, ensuring the system can handle dynamic loads more effectively. Figures 3.6 and 3.7 illustrate the new design of DHIL actuator's arm and the draft sketch with its parameter. The material used is steel.

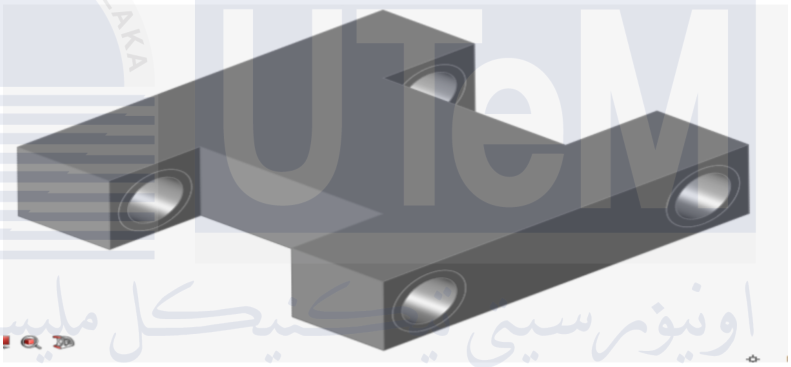


Figure 3.6 Initial Design of DHIL actuator's arm

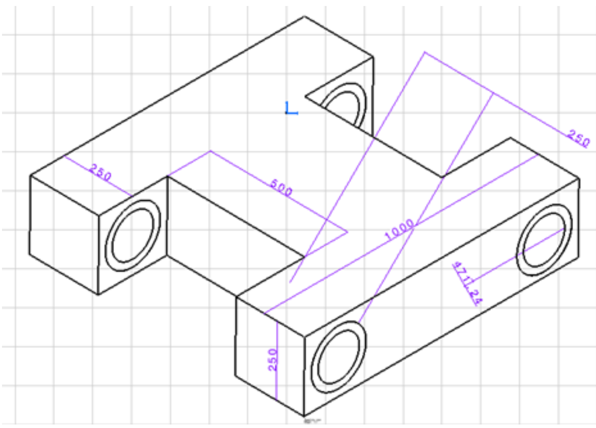


Figure 3.7 Draft sketch of initial DHIL actuator's arm with parameters

3.6 Structural Analysis of Original and Initial Design

The old and initial DHIL actuator's arm was subjected to a detailed structural analysis using Altair Inspire. A force was applied to simulate the dynamic forces encountered during operation, aiming to assess the arm's structural performance, stress distribution, and overall stability.

3.6.1 Structural Analysis of Original Design

The old DHIL actuator's arm was analyzed using Altair Inspire with an applied load of 40,381.5 N to evaluate key structural parameters, including Von Mises stress, factor of safety (FOS), and displacement. The analysis aimed to determine the maximum stress experienced by the arm, ensuring it remains within the material's yield limit. The factor of safety was calculated to verify whether the arm could handle the applied load safely. Additionally, displacement results were assessed to check for excessive deformation that could compromise functionality. These evaluations are critical for identifying areas needing structural improvement.

Here are the following steps of structural analysis of old design of DHIL actuator's arm:

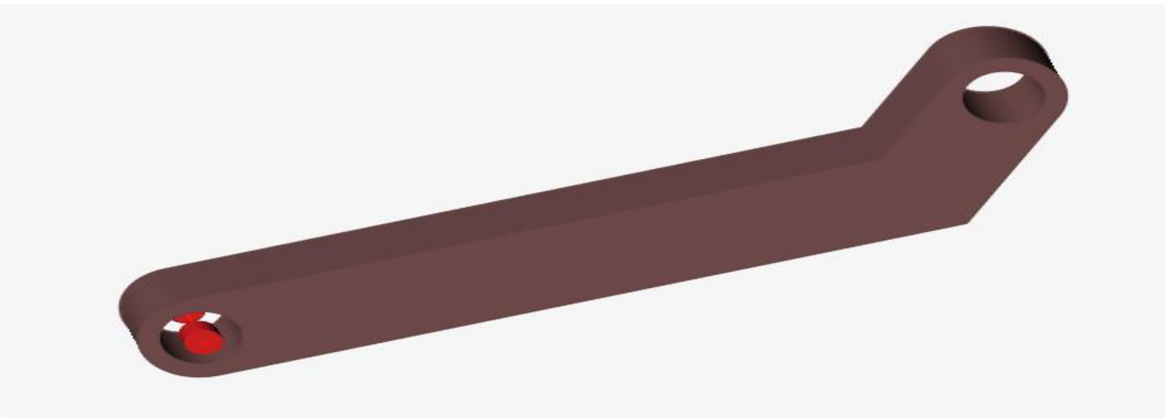


Figure 3.8 Arm Model

The structural analysis of the DHIL actuator's arm began by opening the Arm Model file as shown in Figure 3.8 in Altair Inspire. This initial step ensured that the 3D model of the arm was correctly loaded into the software environment. Once the model was loaded, the units were set to MKS (meter, kilogram, newton, second), ensuring consistency in the measurements throughout the analysis process. Using appropriate units is critical to obtaining accurate results for force, displacement, and stress. Next, the design space was defined as shown in Figure 3.8, which involved specifying the regions of the arm that could undergo material removal during the optimization process. In Altair Inspire, these areas were highlighted in a red-brown color, indicating that they were eligible for topology optimization. This step ensures that only non-essential material is removed, preserving critical areas required for structural integrity.

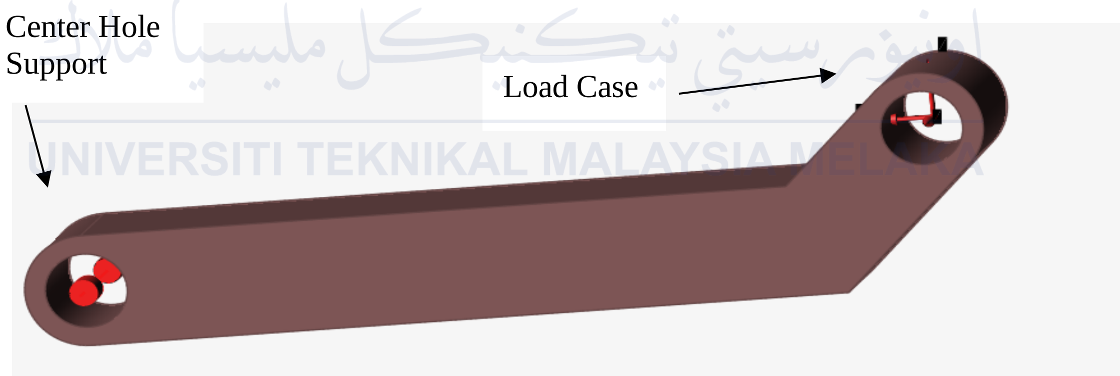


Figure 3.9 Center Hole Support and Load case

Following the definition of the design space, a center hole was created to replicate real-world mounting or connection points shown in Figure 3.9. Supports were applied at key fixed locations, simulating the areas where the arm is rigidly attached to other components. A force of 40,381.5 N was then applied in the X, Y, and Z directions at the appropriate load points, representing the actual forces acting on the arm during dynamic operations. This step is crucial to mimic the operational conditions the arm would experience.

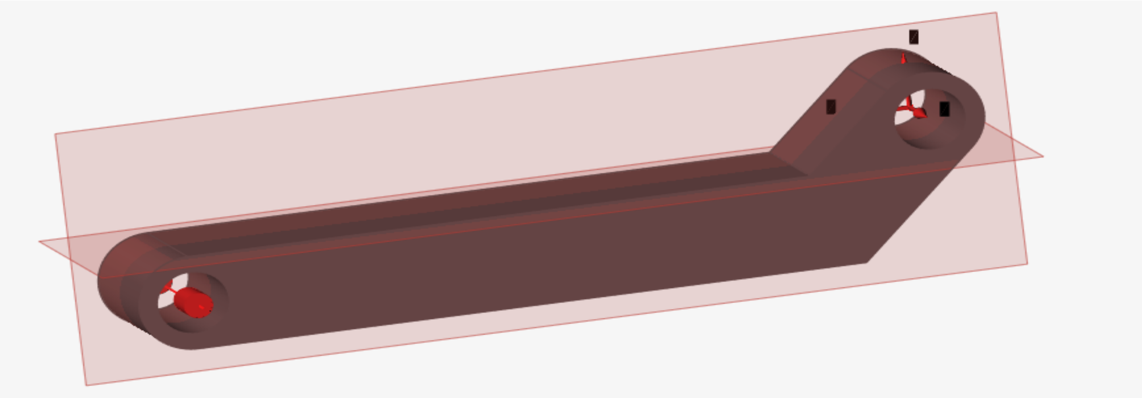


Figure 3.10 Symmetry Plane

Once the load and supports were applied, symmetry planes were added. Two red planes appeared as shown in Figure 3.10, representing symmetry across the X, Y, and Z axes. Applying symmetry planes significantly reduces the computational time by allowing the analysis to focus on a portion of the design while ensuring that the results can be mirrored across the entire arm. This also helps in achieving a balanced and symmetrical design.

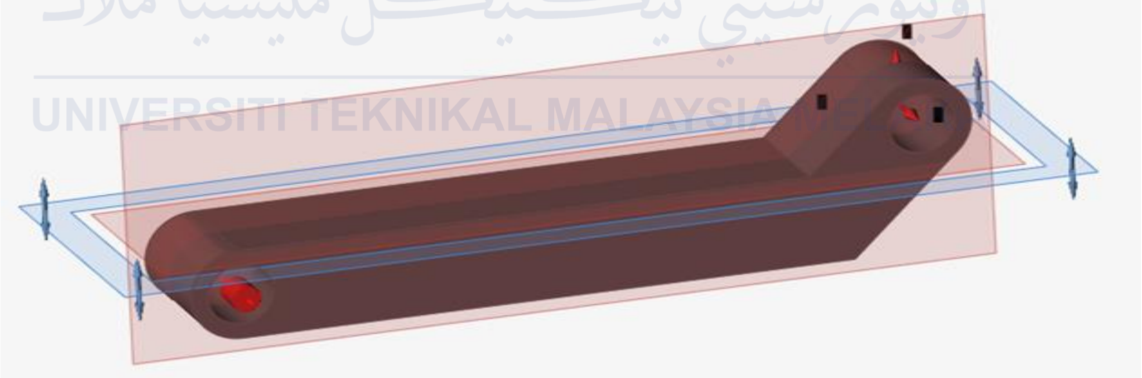


Figure 3.11 Blue planes

After symmetry planes, a draw direction was added, Figure 3.11. Blue planes appeared, indicating the parting direction required for manufacturing processes, such as casting or machining. This ensures that the optimized design can be produced efficiently using available manufacturing techniques.

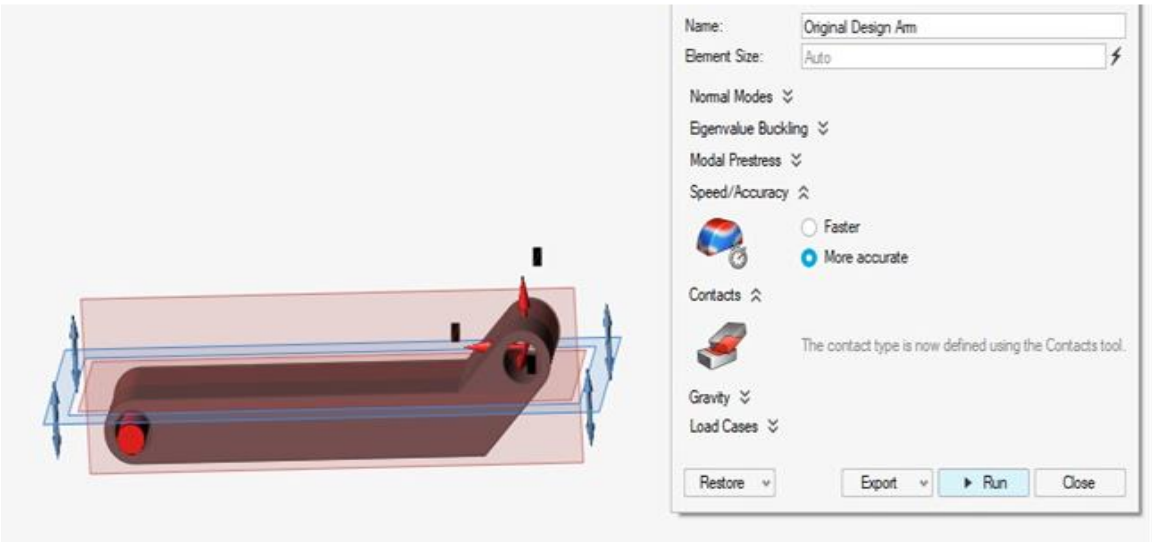


Figure 3.12 Static Analysis

Finally, a static analysis was conducted as shown in Figure 3.12 to evaluate the arm's performance under the given load. The analysis provided critical results, including Von Mises stress, which indicates whether the material remains within its yield strength, factor of safety, which ensures the arm can handle loads safely, and displacement, which measures the amount of deformation under load. These results offer valuable insights into the arm's structural behavior and highlight areas for potential improvement in future designs.

3.6.2 Structural Analysis of Initial Design

The old DHIL actuator's arm was analyzed using Altair Inspire with an applied load of 80763N to evaluate key structural parameters, including Von Mises stress, factor of safety (FOS), and displacement. The analysis aimed to determine the maximum stress experienced by the arm, ensuring it remains within the material's yield limit. The factor of safety was calculated to verify whether the arm could handle the applied load safely. Additionally, displacement results were assessed to check for excessive deformation that could compromise functionality. These evaluations are critical for identifying areas needing structural improvement.

Here is the structural analysis of initial DHIL actuator's arm steps:

The structural analysis of the initial design of the DHIL actuator's arm was performed using Altair Inspire, with a load of 80,763 N applied to simulate extreme operational conditions. The analysis began by opening the arm model shown in Figure 3.13 and setting the units to MKS (meter, kilogram, newton, second) for consistency. The design space was defined in Figure 3.14, with the red-brown areas indicating regions eligible for material removal in the topology optimization process.

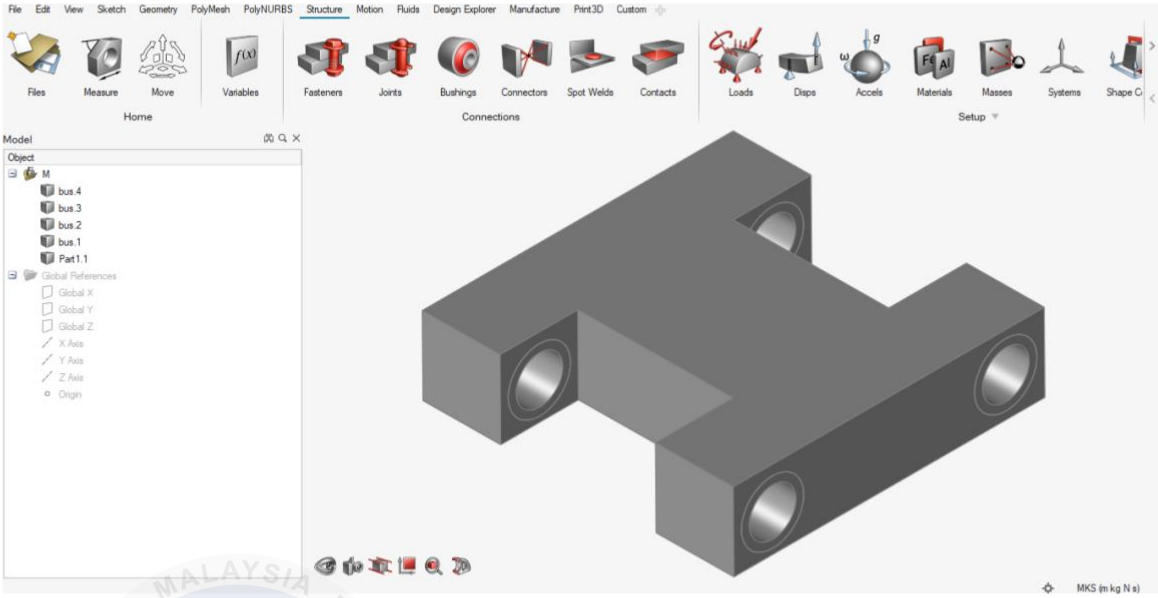


Figure 3.13 Arm Model

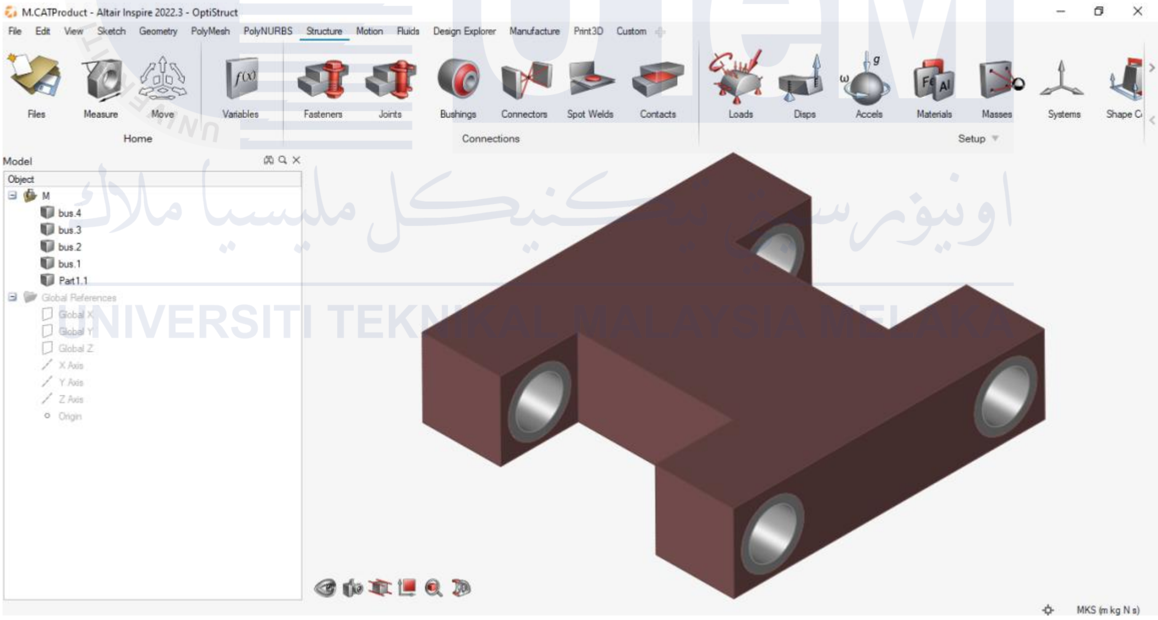


Figure 3.14 Design Space

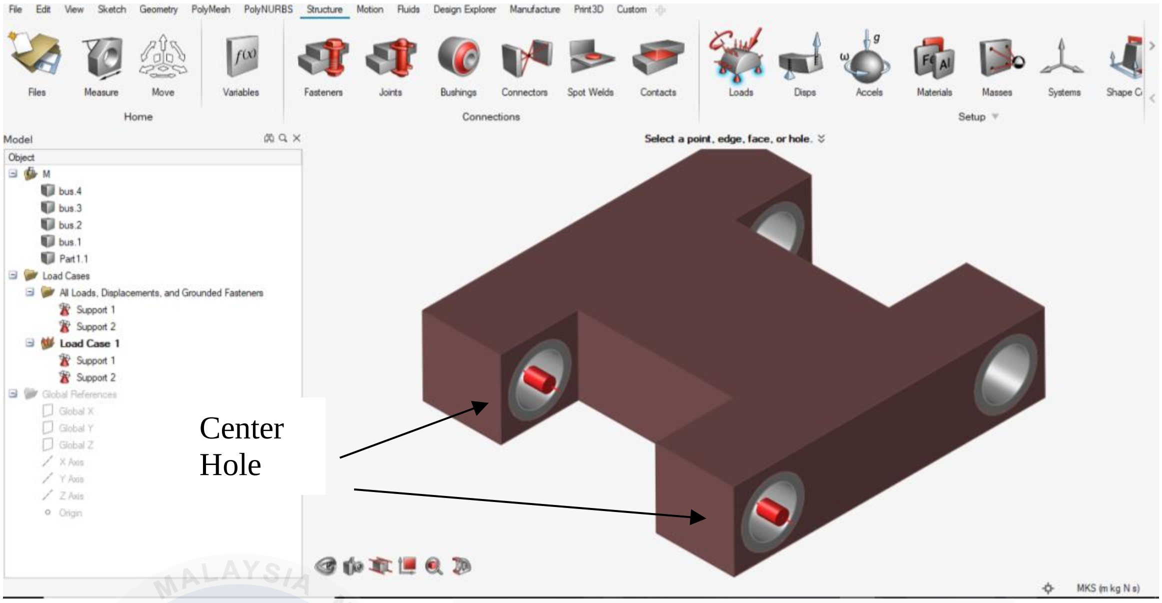


Figure 3.15 Center Hole

A center hole was created to replicate mounting or attachment points as shown in Figure 3.15. Supports were applied at specific locations to represent the fixed points of the actuator arm. The load of 80,763 N was applied in the X, Y, and Z directions as shown in Figure 3.16, representing the forces exerted during towing and hauling operations. This high load value ensures that the analysis captures the arm’s behavior under maximum stress conditions.

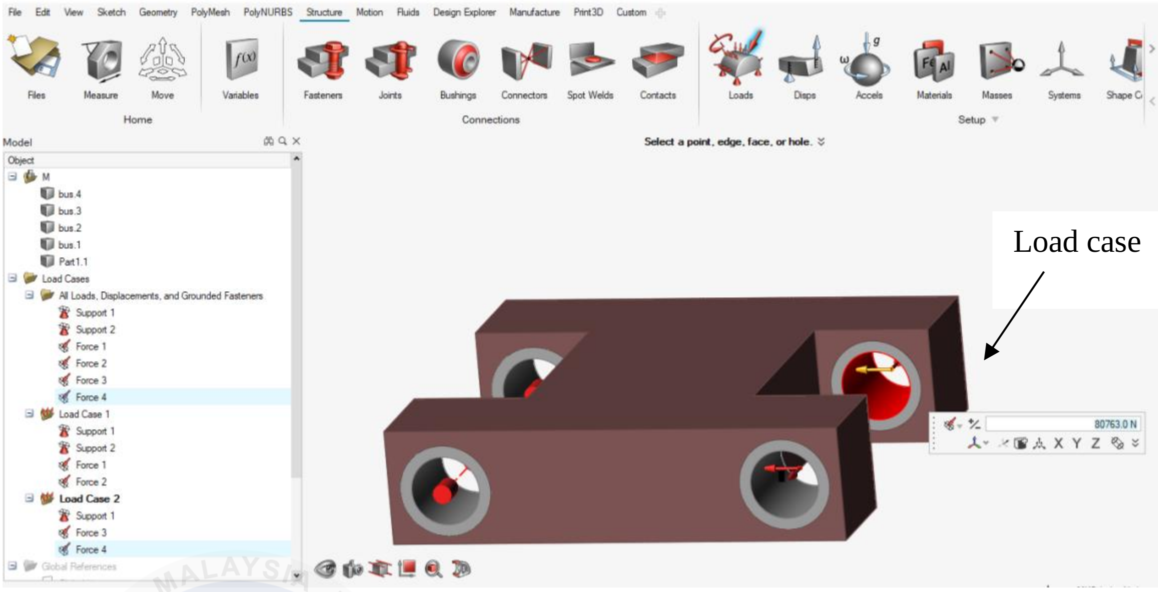


Figure 3.16 Load case

After applying supports and forces, symmetry planes as shown in Figure 3.17 were added until three red planes appeared, ensuring symmetry along all axes. This step reduces the computational effort and guarantees a balanced design. Additionally, a draw direction as shown in Figure 3.18 was added until blue planes appeared, representing the required parting direction for manufacturing, ensuring the design can be produced using standard techniques.

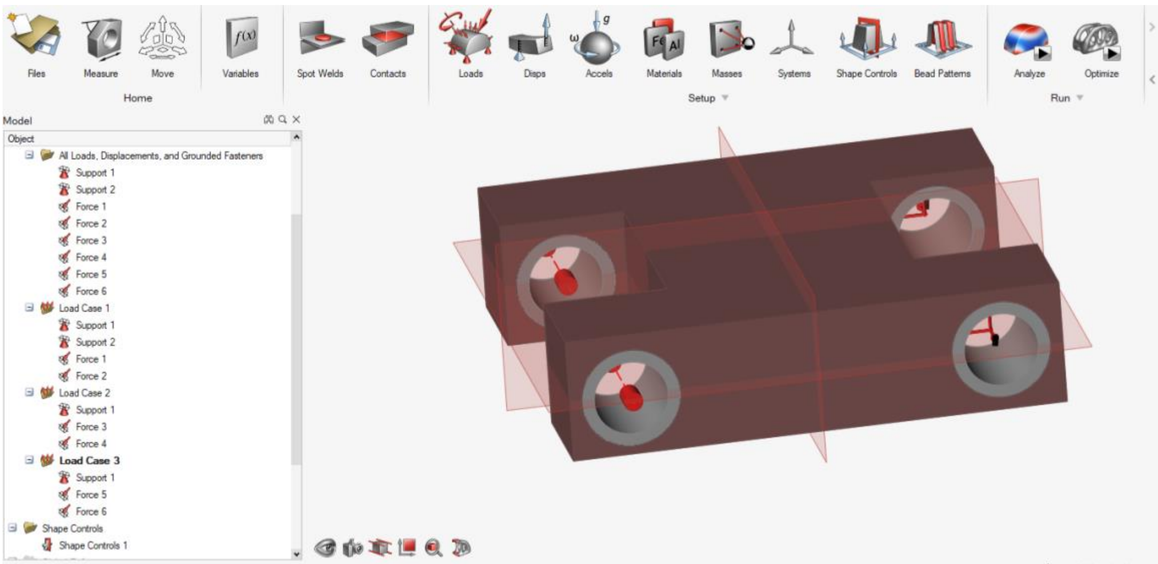


Figure 3.17 Symmetry Plane

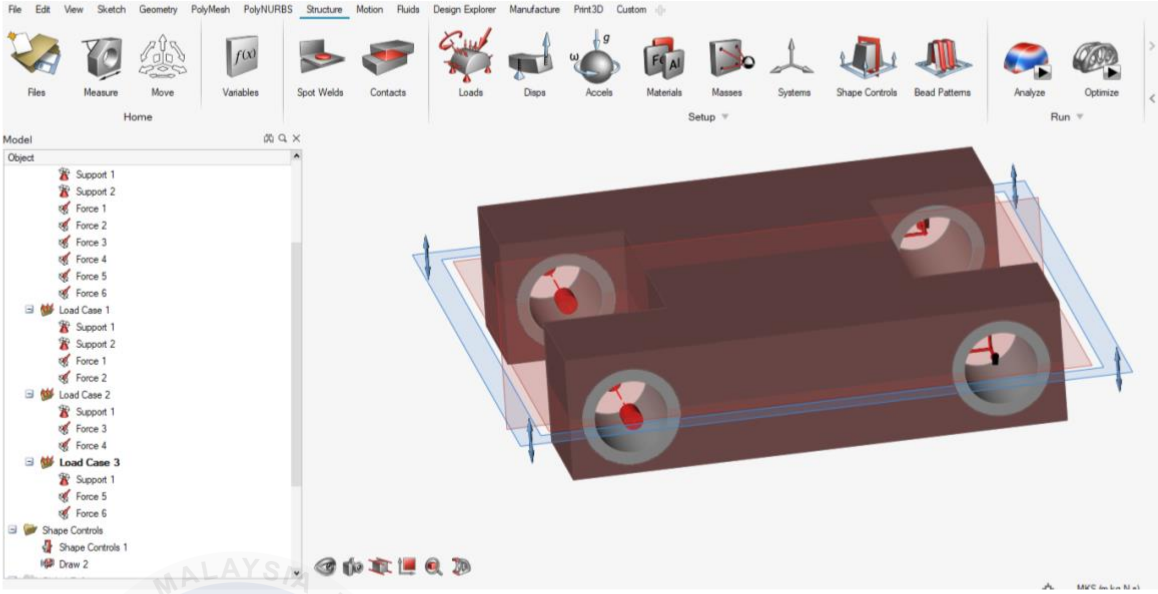


Figure 3.18 Draw Directions

Finally, a static analysis as shown in figure 3.19 was conducted to assess key structural parameters such as Von Mises stress, factor of safety, and displacement. The results provided insights into the arm's structural performance, highlighting critical areas that experience high stress and deformation, which can guide the optimization process for the final design.

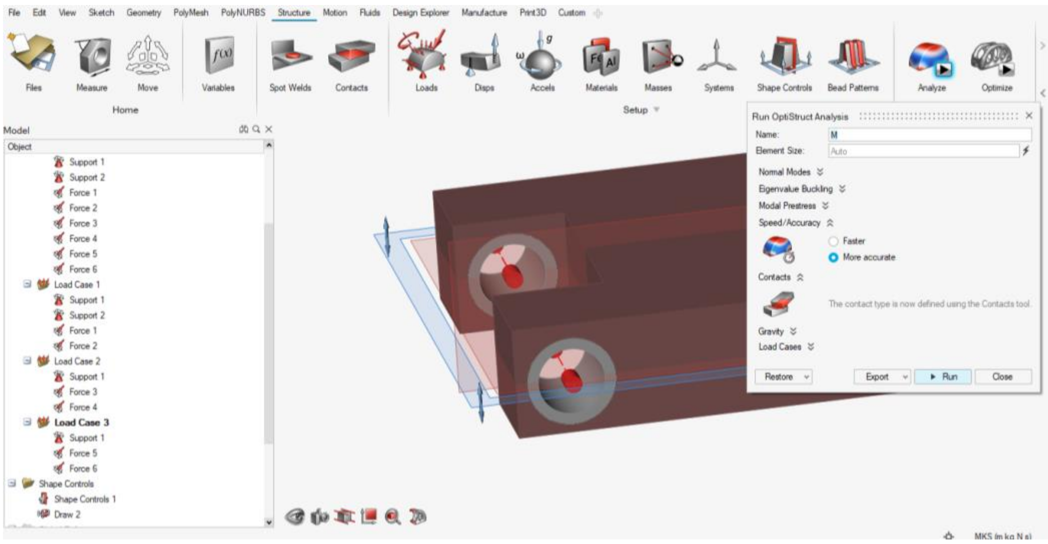


Figure 3.19 Static Analysis

3.7 Structural Analysis Result

The structural analysis of the old and initial DHIL actuator's arm was conducted using Altair Inspire for load cases in the X, Y, and Z. The key results obtained from the analysis include displacement, Von Mises stress, and the factor of safety (FOS) for each load case.

3.7.1 Structural Analysis Result for Original Design

The structural analysis results for original design of DHIL actuator's arm for each load case X, Y, and Z are shown in details in the Table 3.1.

Table 3.1 Results of Original Design

Design Type	Load Case	Von Mises Stress (MPa)	Displacement (mm)	Factor of Safety
Original Design	X	1735.0	2.147	0.10
	Y	691.70	1.036	0.30
	Z	3834.0	5.490	0.05

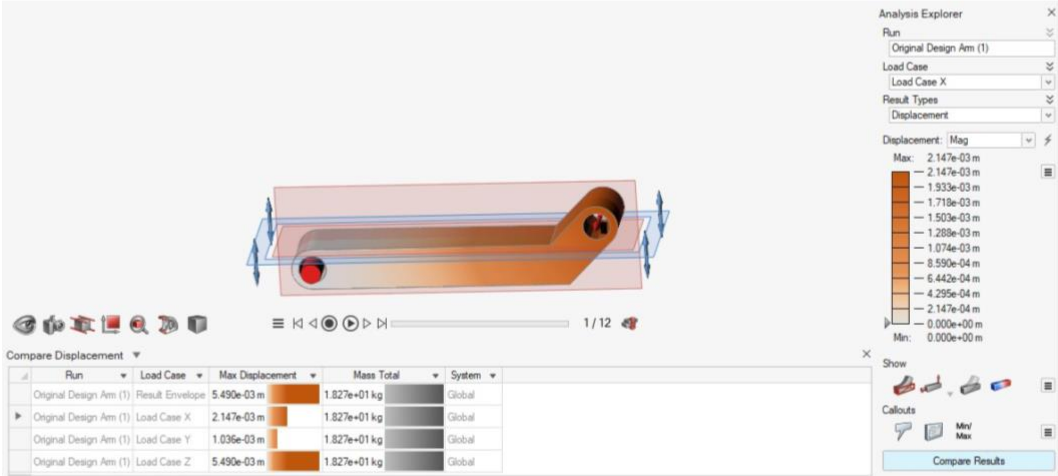


Figure 3.20 Displacement Result of Original Design

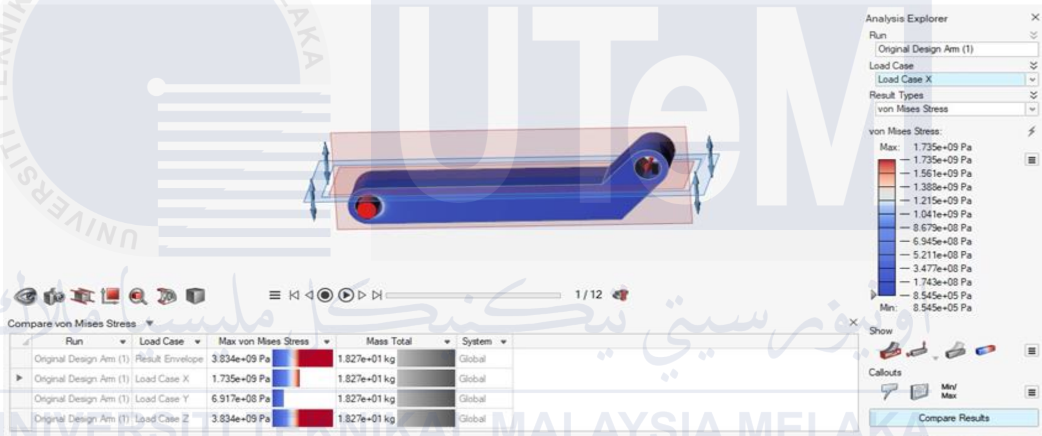


Figure 3.21 Von Mises Stress Result of Original Design

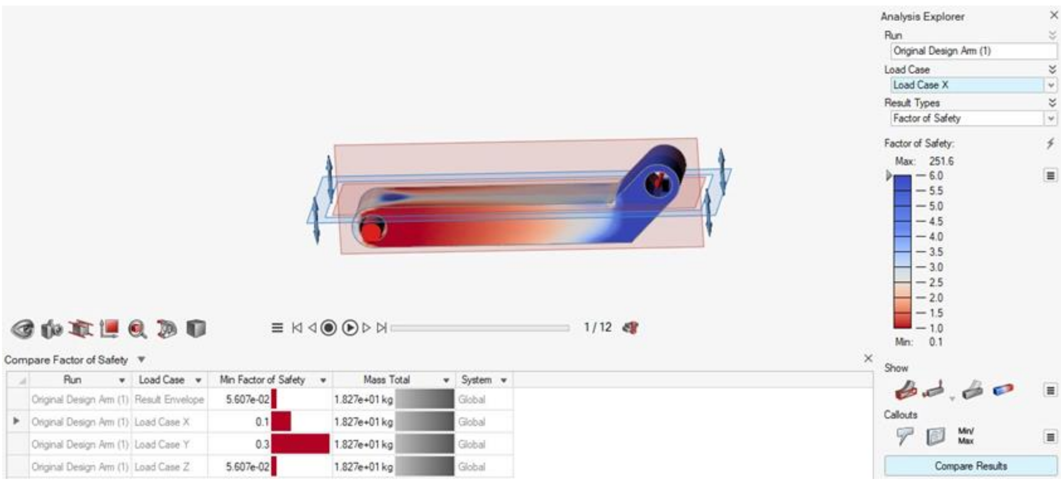


Figure 3.22 Factor of Safety of original Design

The structural analysis of the original design under different load cases (X, Y, and Z) reveals significant areas of concern. For displacement as shown in Figure 3.20, the maximum values recorded are 2.147 mm, 1.036 mm, and 5.49 mm for load cases X, Y, and Z, respectively. The displacement plots show deformation concentrated in specific regions, with red zones highlighting the areas with the highest movement. For Von Mises stress as shown in Figure 3.21, the maximum values are 1735 MPa, 691.7 MPa, and 3834 MPa for load cases X, Y, and Z, respectively, indicating critical stress concentration points, especially in load case Z. The factor of safety analysis as shown in Figure 3.22, reveals minimal values of 0.1, 0.3, and 0.05067 for load cases X, Y, and Z, respectively, with extensive red zones suggesting high risk of failure in multiple regions. Overall, the original design struggles to handle the applied loads effectively, as shown by its high stress and low safety margins.

3.7.2 Structural Analysis Result for Initial Design

The structural analysis results for initial design of DHIL actuator's arm for each load case X, Y, and Z are shown in details in the Table 3.2.

Table 3.2 Results of Initial Design

Design Type	Load Case	Von Mises Stress (MPa)	Displacement (mm)	Factor of Safety
Initial Design	X	77.00	0.08161	2.8
	Y	21.97	0.01246	9.8
	Z	181.70	0.64410	1.2

The new design demonstrates significant improvements in displacement, stress, and safety factor across all load cases. For displacement as shown in Figure 3.23, the maximum values are reduced to 0.08161 mm, 0.01246 mm, and 0.617 mm for load cases X, Y, and Z, respectively. The images show minimal deformation, with red zones confined to small areas. For Von Mises stress as shown in Figure 3.24, the maximum values are drastically reduced to 77 MPa, 21.97 MPa, and 181.7 MPa for load cases X, Y, and Z, respectively, indicating better load distribution and fewer critical stress points. The factor of safety as shown in Figure 3.25 is significantly improved, with minimum values of 2.8, 9.8, and 1.2 for load cases X, Y, and Z. The safety plots show extensive green zones, demonstrating a much more reliable and stable structure under all loading conditions.

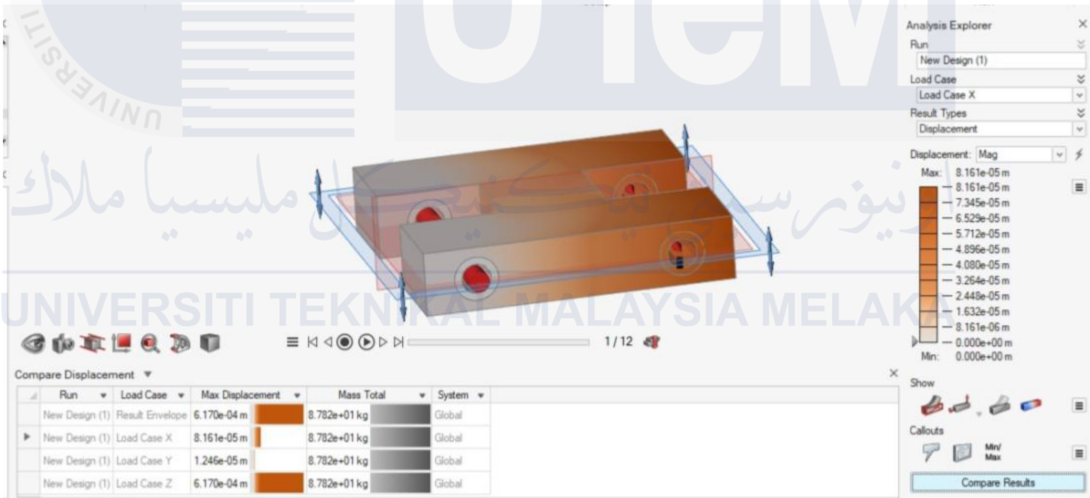


Figure 3.23 Displacement Result of Initial Design

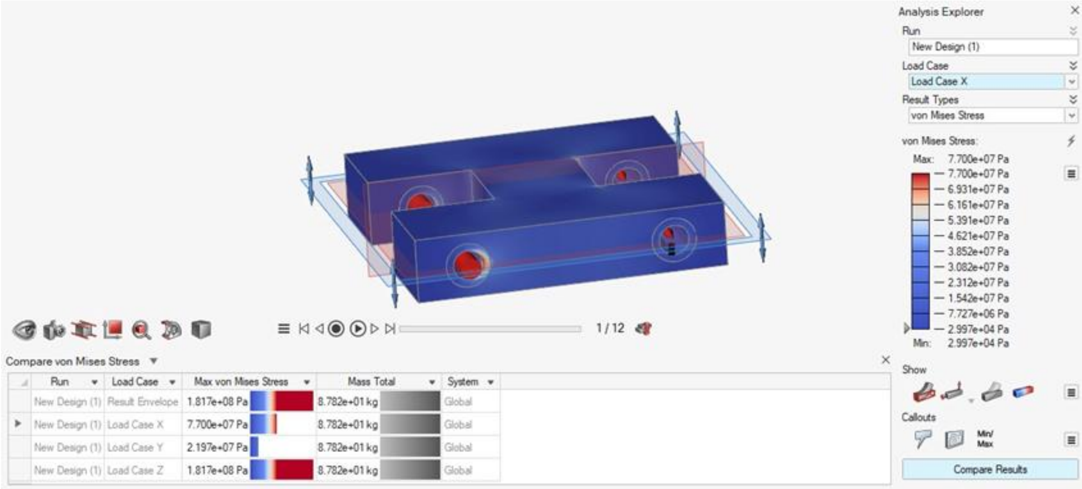


Figure 3.24 Von Mises Stress Result of Initial Design

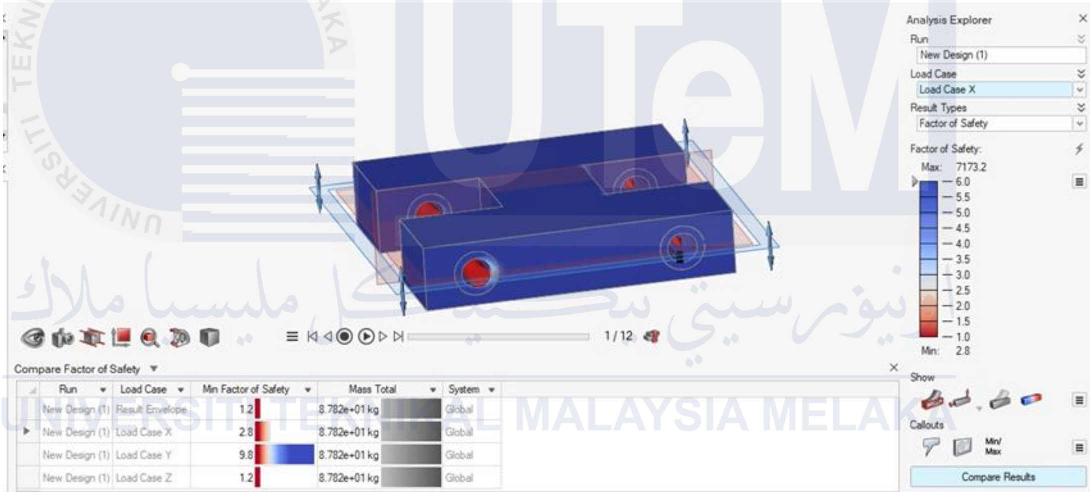


Figure 3.25 Factor of Safety Result of Initial Design

3.8 Summary

This chapter focuses on the methodology used for the structural optimization of the DHIL actuator. It includes a detailed review of the baseline study, design parameters, and structural analysis of both the old and initial designs. The chapter then moves on to the application of topology optimization techniques to improve the actuator's performance, followed by the creation of the optimized design. The analysis results, including Von Mises stress, displacement, and factor of safety, are compared to evaluate the improvements in the design.

CHAPTER 4

OPTIMIZATION OF DHIL ACTUATORS

4.1 Introduction

This chapter focuses on the optimization process of the Dynamic Hitch Lift Controller (DHIL) actuator to improve its structural performance and efficiency. The process begins with the topology optimization of the old and initial designs. The results of topology optimization are presented, followed by the recreation of the optimized design using CATIA software.

Subsequently, a structural analysis is performed on the optimized design to evaluate its performance under loading conditions. Afterward, topology optimization of the optimized design is carried out to further refine the structure. This process leads to the redesign of the optimized DHIL actuator, ensuring manufacturability and functionality.

Finally, a comparative analysis of finite element analysis (FEA) results is conducted, highlighting the percentage improvements achieved in terms of von mises stress, displacement, and factor of safety. This comprehensive approach ensures the final design meets both performance and operational requirements.

4.2 Topology Optimization of Initial Design

After completing the static structural analysis, including the application of supports, forces, symmetry planes, and setting the final draw direction, the process proceeded with the topology optimization of the initial design using the in Altair Inspire. This step aimed to refine the structure by achieving the best balance between minimizing weight and maintaining stiffness. From the same window in Inspire, after completing the structural analysis, topology optimization was run with a mass target of 30% of the total design volume as shown in Figure 4.1. This approach ensured that unnecessary material was removed while maintaining the required structural performance. Figures 4.2 illustrate the optimization process.

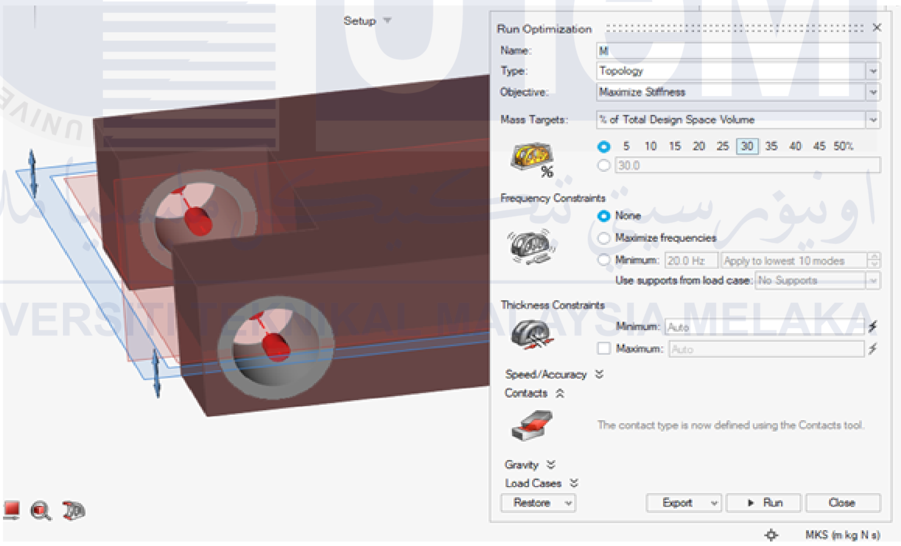


Figure 4.1 Run Topology Optimization

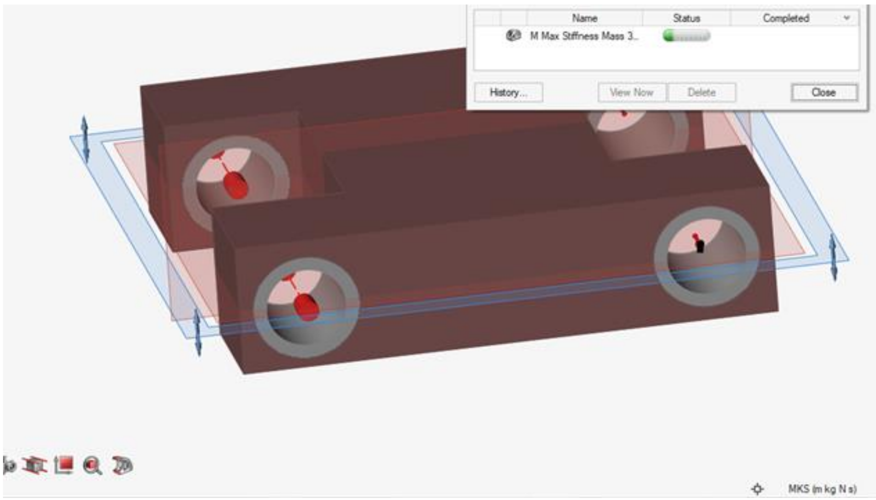


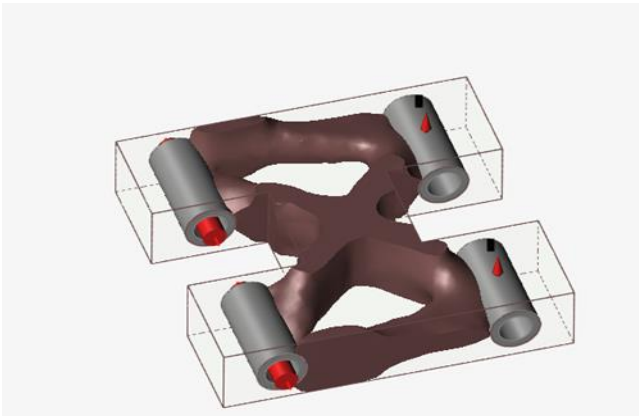
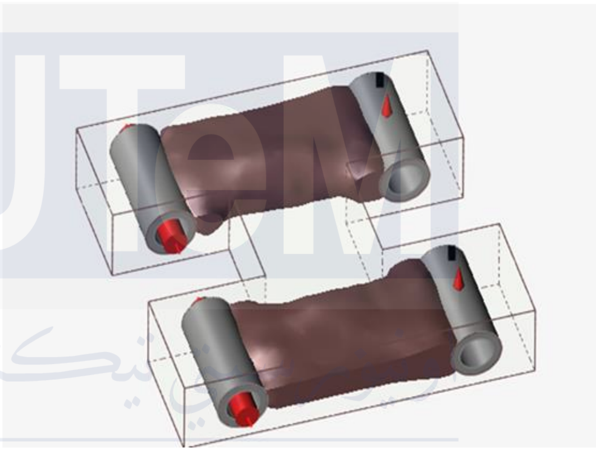
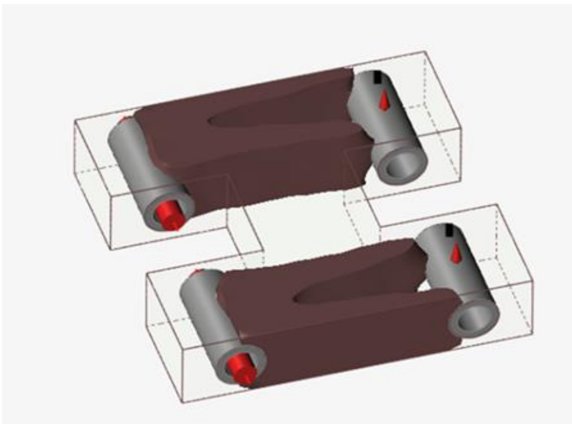
Figure 4.2 Optimization Process

4.3 Topology Optimization Result of Initial Design

The topology optimization result of the initial DHIL actuator design showed a significant reduction in material usage while retaining essential load-bearing structures. With a mass target of 30%, the optimization effectively removed non-critical material from low-stress regions, resulting in a lighter and more efficient design.

Key observations from the result include the presence of clearly defined load paths where material was retained to ensure structural integrity. Additionally, areas experiencing minimal stress were significantly reduced or eliminated, highlighting the potential for weight reduction without compromising performance. These results demonstrate that the design can be further refined for manufacturability while achieving improved stiffness and strength. Table 4.1 shows the state of initial design of each load case X, Y and Z after topology optimization process.

Table 4.1 State of Initial Design

Load Case X	
Load Case Y	
Load Case Z	

4.4 Recreate Optimize Design

The recreated optimized design is developed based on the results obtained from the topology optimization of the initial DHIL actuator design. This process involves translating the optimized shape into a manufacturable model while ensuring that critical structural features are retained. Based on the topology optimization result obtained from the initial DHIL actuator design, the next step involved recreating the optimized design using CATIA software. Figure 4.3 and 4.4 shows the optimize design in CATIA draft sketch with its parameter and optimize design model part in CATIA. The parameter for the optimized design still as same as the parameter of original and initial design.

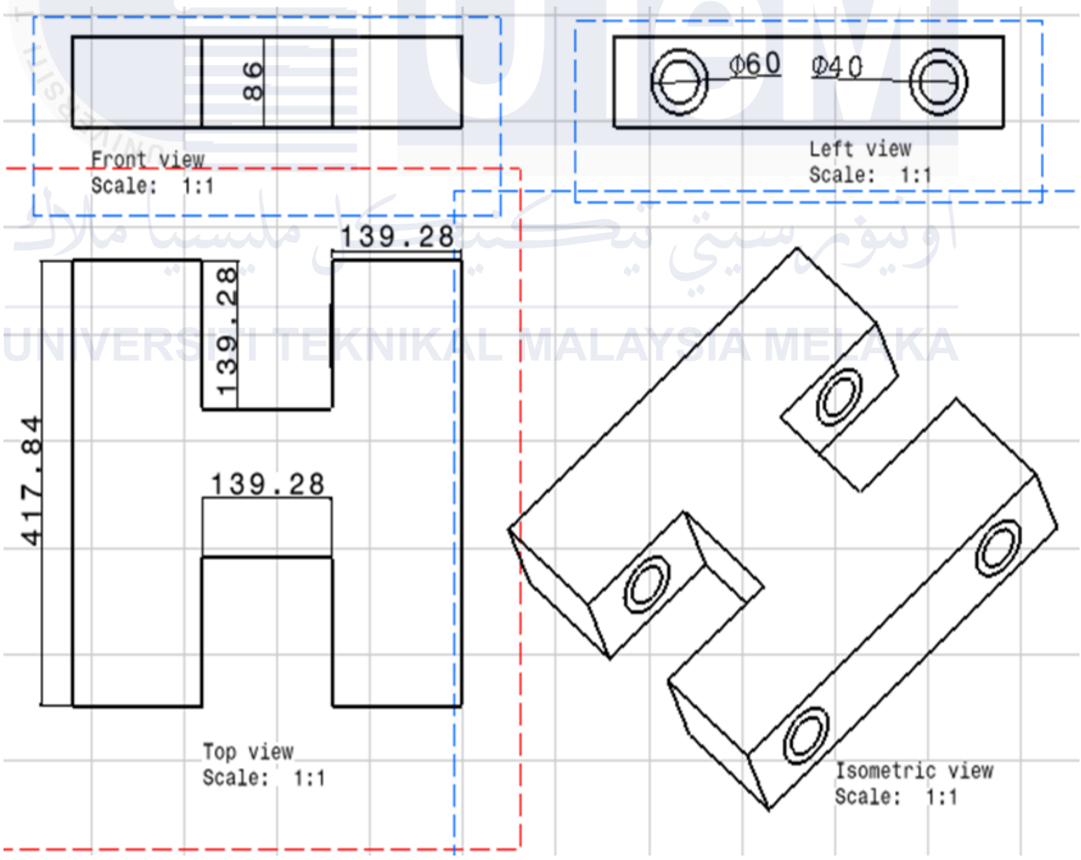


Figure 4.3 Draft Sketch of Optimize Design

4.5 Structural Analysis of Optimize Design

The structural analysis for the optimized design follows the same steps and processes as performed for the initial design. Using Altair Inspire, the optimized model is analyzed under identical load conditions, ensuring a consistent evaluation of performance. Fixed supports are applied at the same mounting points, and a force of 80,763 N is applied in the X, Y, and Z directions. The same symmetry constraints and draw direction are set to reflect realistic manufacturing and operating conditions. After running the static analysis, results such as displacement, Von Mises stress, and factor of safety (FOS) are evaluated to compare the performance of the optimized design with the original and initial design. Table 4.2 shows the detail result of structural optimization for optimize design.

Table 4.2 Results of Optimize Design

Design Type	Load Case	Von Mises Stress (MPa)	Displacement (mm)	Factor of Safety
Optimize Design	X	80.26	0.08555	2.7
	Y	25.70	0.01501	8.4
	Z	199.80	0.64410	1.1

The optimized design further enhances the performance of the structure, though the improvements are more incremental compared to the transition from the original to the new design. For displacement as shown in Figure 4.4, the maximum values are 0.08555 mm, 0.01501 mm, and 0.6441 mm for load cases X, Y, and Z, respectively.

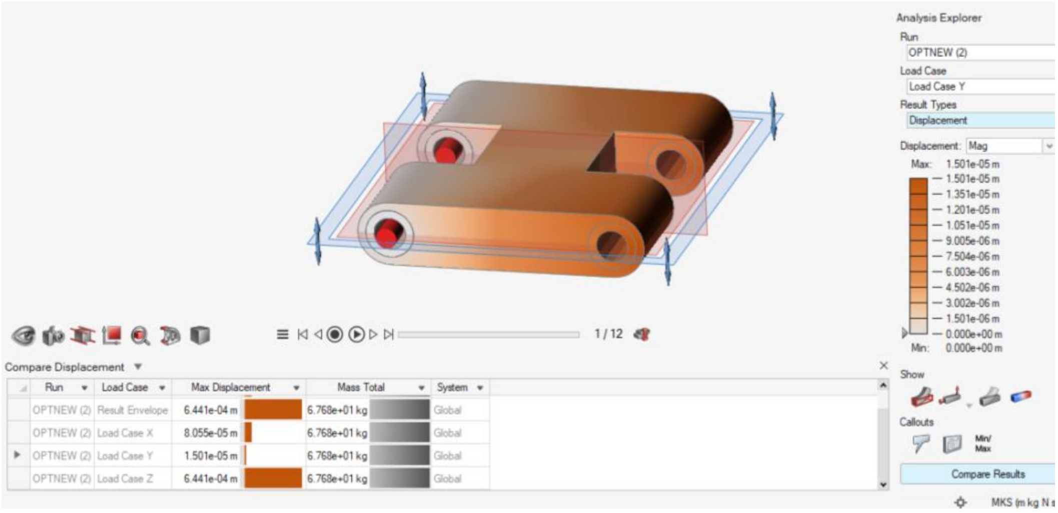


Figure 4.4 Displacement Result of Optimize Design

While slightly higher than the new design, the displacement remains minimal, with deformation concentrated in specific zones. For Von Mises stress as shown in Figure 4.5, the maximum values are 80.26 MPa, 25.7 MPa, and 199.8 MPa for load cases X, Y, and Z, respectively, indicating controlled stress distribution with safe margins.

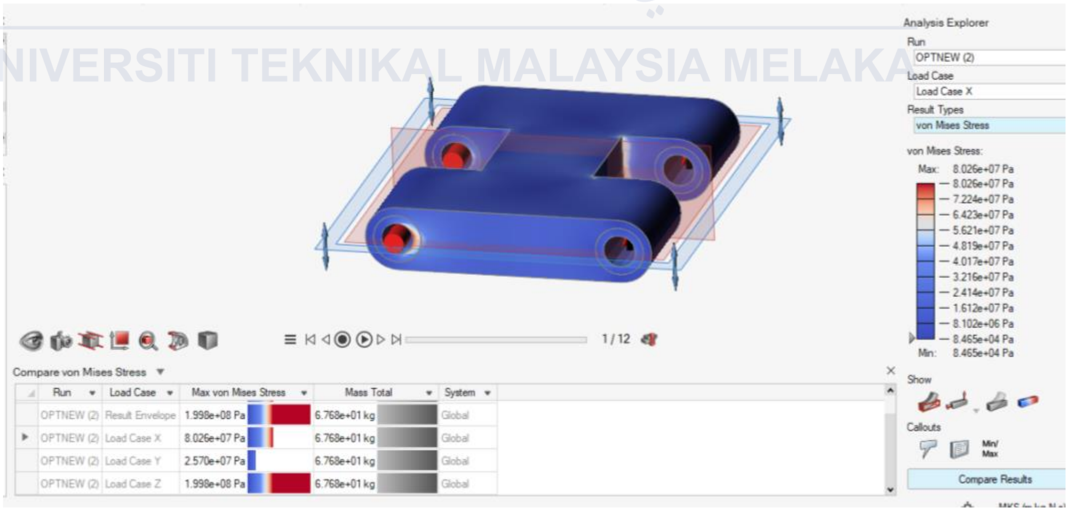


Figure 4.5 Von Mises Stress of Optimize Design

The factor of safety analysis in Figure 4.6 shows minimum values of 2.7, 8.4, and 1.1 for load cases X, Y, and Z. The safety plots retain predominantly green zones, with only a few areas showing moderate risk under load.

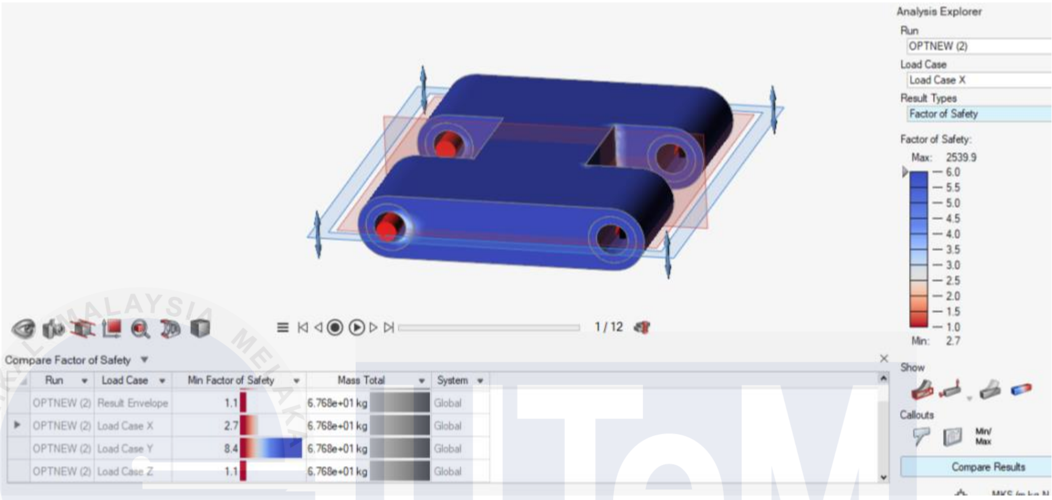


Figure 4.6 Factor of Safety Result of Optimize Design

4.6 Topology Optimization of Optimize Design

Following the structural analysis of the optimized DHIL actuator design, a second round of topology optimization was performed using Altair Inspire. The purpose of this step was to further refine the design by removing any remaining non-essential material, ensuring maximum stiffness with minimal weight. The same method was applied, with a mass target of 30% of the remaining design volume. Constraints such as symmetry and draw direction were maintained to ensure manufacturability. The resulting design provided a lighter, stronger, and more efficient actuator arm. Figure 4.4 shows the result optimize design after topology optimization process.

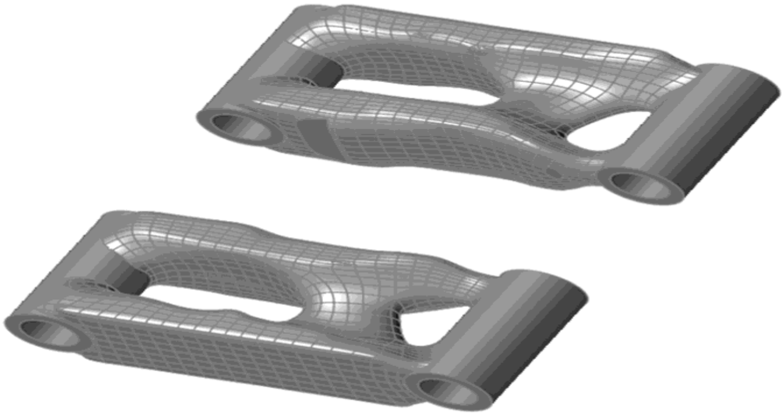


Figure 4.7 Result of Optimize Design

4.7 Redesign Optimize Design

Following the completion of topology optimization in Altair Inspire, the design was recreated and further refined in CATIA to ensure manufacturability. In this stage, the optimization results were translated into a 3D CAD model, where geometry was adjusted for practical manufacturing processes. Smooth curves were introduced to reduce stress concentration, while fillets were applied to enhance strength and durability. Wall thickness was uniformed to ensure consistency during fabrication. The final optimizes design model as shown in Figure 4.5 was checked for structural integrity, load-bearing capacity, and manufacturability, ensuring it meets both performance and production standards. Figure 4.6 shows the draft sketch of final optimize design with its parameter.

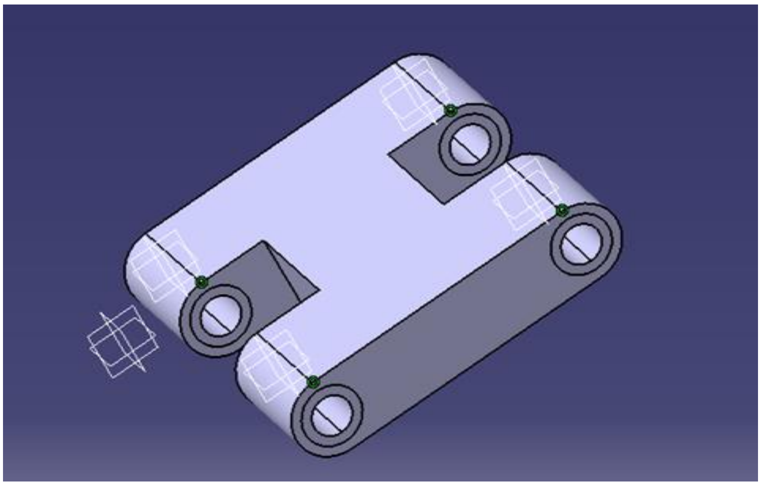


Figure 4.8 Final Optimize Design Model

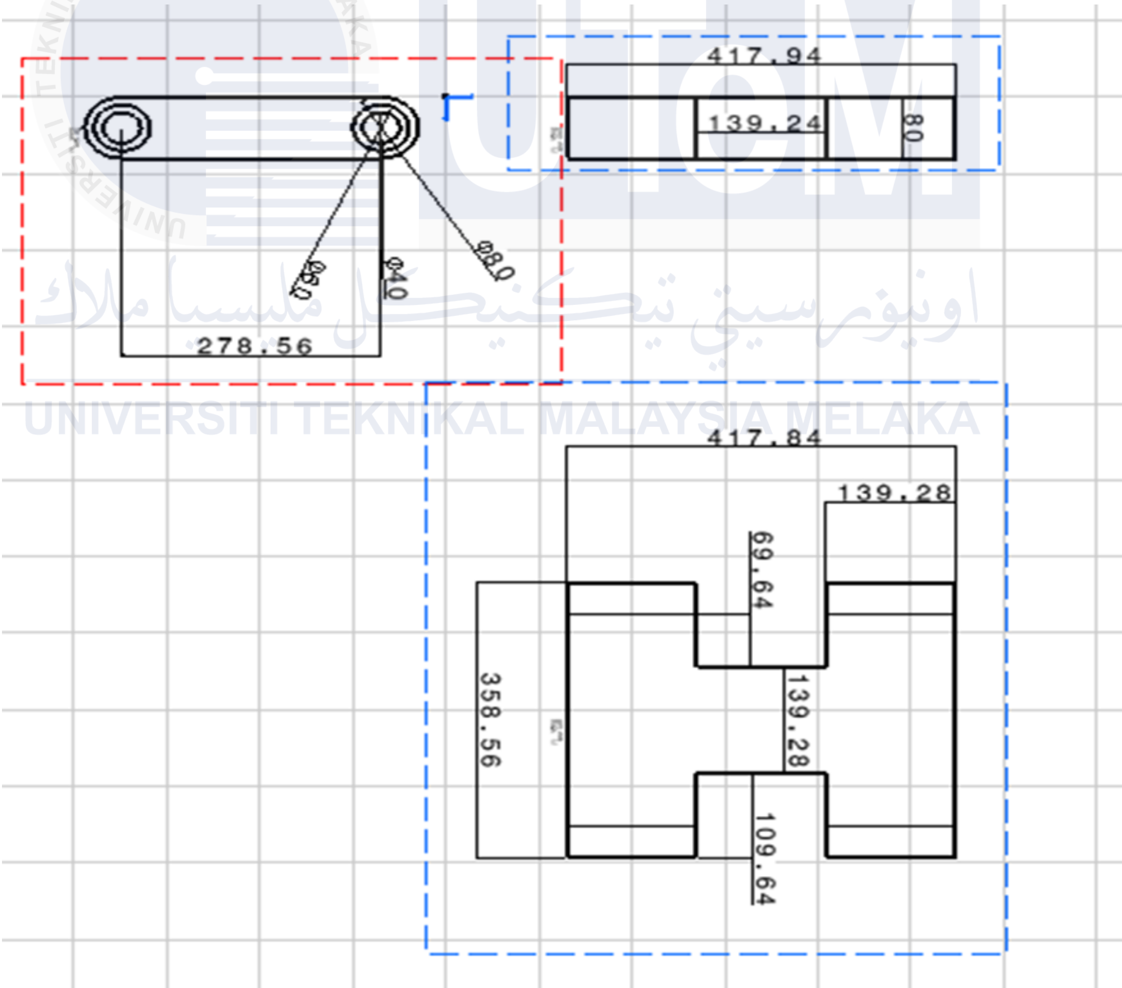


Figure 4.9 Draft Sketch of Final Optimize Design

4.8 Comparison of FAE Result

This section compares the FEA results for the original, initial and optimized designs of the DHIL actuator, focusing on key performance indicators. Von Mises Stress analysis reveals improved load distribution in the optimized design, with lower stress concentrations. The displacement analysis shows reduced deformation in the optimized design, indicating increased stiffness. Additionally, the factor of safety (FoS) is higher in the optimized design, suggesting better structural reliability. Table 4.3 shows the details comparison of FAE results of original design, initial design and optimized design for each load case X, Y and Z.

The percentage improvements highlight the effectiveness of the optimization process in enhancing overall design performance. The Von Mises Stress Improvement is a crucial metric used to assess how much the stress in the design has been reduced compared to the original design. This improvement is calculated by comparing the original Von Mises stress value with the new or optimized stress value. The formula used for calculating this improvement is:

Von Mises Stress Improvement (%) =

$$\frac{\text{Original Von Mises Stress} - \text{New/Optimized Von Mises Stress}}{\text{Original Von Mises Stress}} \times 100$$

Displacement improvement is another key factor that measures how much the deformation of the actuator has been minimized in the optimized design compared to the original. The displacement refers to the amount of movement or deformation that occurs when the actuator is subjected to forces. The percentage improvement in displacement is calculated using the formula:

Displacement Improvement (%) =

$$\frac{(\text{Original Displacement} - \text{New/Optimized Displacement})}{\text{Original Displacement}} \times 100$$

The Factor of Safety (FoS) is a measure of the safety margin in the design, indicating how much stronger the design is compared to the expected load. Improving the Factor of Safety is essential for enhancing the safety and reliability of the design. The percentage improvement in the Factor of Safety is calculated using the following formula:

Factor of Safety Improvement (%) =

$$\frac{(\text{New/Optimized Factor of Safety} - \text{Original Factor of Safety})}{\text{Original Factor of Safety}} \times 100$$

Table 4.3 Comparison of FAE results

Design Type	Load Case	Von Mises Stress (MPa)	Displacement (mm)	Factor of Safety	Von Mises Stress Improvement (%)	Displacement Improvement (%)	Factor of Safety Improvement (%)
Original Design	X	1735.00	2.14700	0.10000	-	-	-
Original Design	Y	691.70	1.03600	0.30000	-	-	-
Original Design	Z	3834.00	5.49000	0.05067	-	-	-
New Design	X	77.00	0.08161	2.80000	95.56	96.20	2700.00
New Design	Y	21.97	0.01246	9.80000	96.82	98.80	3166.67
New Design	Z	181.70	0.61700	1.20000	95.26	88.76	2268.27
Optimized Design	X	80.26	0.08555	2.70000	95.37	96.02	2600.00
Optimized Design	Y	25.70	0.01501	8.40000	96.28	98.55	2700.00
Optimized Design	Z	199.80	0.64410	1.10000	94.79	88.27	2070.91

The results from the FAE comparison table indicate that the topology optimization process applied to the original design successfully enhanced the structural performance of the Dynamic Hitch Lift (DHIL) actuator. Starting with the topology optimization of the original design, an initial design was created and further refined through additional structural analysis and optimization. This iterative process led to notable improvements in key performance metrics, including mechanical strength, displacement reduction, and safety margins.

The optimized design showed a significant decrease in Von Mises stress and displacement compared to the original design, with improvements exceeding 95% in most load cases. Additionally, the Factor of Safety increased considerably, demonstrating the improved load-bearing capacity and overall reliability of the actuator. These improvements validate that the methodology of performing structural analysis combined with topology optimization was effective in refining the actuator's structure, enhancing its mechanical strength while simultaneously minimizing its weight.

Overall, the optimization process achieved the primary objective of this project by producing a lighter, stronger, and safer DHIL actuator. The final design is better equipped to handle dynamic loads and offers improved performance in real-world applications, making it a more reliable and efficient solution for towing, hauling, and other related operations.

4.9 Summary

This chapter focused on optimizing the design of the Dynamic Hitch Lift Controller (DHIL) actuator using topology optimization techniques to enhance its performance, stability, and efficiency. The chapter began with an in-depth analysis of the original and initial designs, followed by the application of structural analysis to evaluate their behavior under specific load cases. With the baseline results established, topology optimization was then applied. This process significantly improved the actuator's performance by reducing Von Mises stress, minimizing displacement, and increasing the Factor of Safety.

After the topology optimization process, the optimized designs were compared with the original ones, showing clear improvements in terms of reduced stress, better structural stability, and higher safety margins. The optimized design also exhibited a substantial reduction in displacement, leading to more precise control and better load handling capabilities. The final step involved redesigning the optimized structure, followed by additional structural analysis to ensure that the changes resulted in superior performance.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The optimization process for the Dynamic Hitch Lift (DHIL) actuator was successfully conducted, resulting in significant improvements in structural performance and efficiency. By employing topology optimization techniques, the project achieved notable reductions in weight and displacement while enhancing the factor of safety. The final optimized design demonstrated improved stress distribution, better structural integrity, and enhanced energy efficiency. Comparative analysis of the original, initial, and optimized designs validated the effectiveness of the methodology, highlighting substantial performance improvements and greater reliability. These results confirm that the optimization approach not only met but exceeded the project's objectives, making the DHIL actuator a more efficient and reliable solution for real-world applications.

5.2 Recommendation

Based on the findings, several recommendations are proposed. Further iterations of topology optimization can be explored to achieve even greater material efficiency without compromising structural strength. The use of lightweight, high-strength materials should be considered to enhance performance while reducing overall weight. Real-world testing under various conditions is recommended to validate the design's reliability and functionality in diverse environments. Additionally, integrating advanced control algorithms for dynamic real-time adjustments can further improve operational efficiency. The DHIL actuator's adaptability to other industries, such as aerospace and robotics, should also be investigated to expand its application. Lastly, incorporating energy recovery mechanisms could enhance the system's sustainability and make it even more resource-efficient. These recommendations aim to build upon the project's success and pave the way for future advancements.

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APPENDICES

APPENDIX A Gantt Chart BDP 1

WEEK/ ACTIVITY	Planning/ Actual	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project planning and innitiation	P														
	A														
Baseline study	P														
	A														
Initial design creation	P														
	A														
Structural analysis of original and initial design	P														
	A														
Topology Optimization of initial design	P														
	A														
Optimize design creation	P														
	A														
Structural analysis	P														
	A														
Refinement Optimization	P														
	A														

APPENDIX B Gantt Chart BDP 2

WEEK/ ACTIVITY	Planning/ Actual	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Final design development	P														
	A														
Comparative analysis	P														
	A														
Documentation and report preparation	P														
	A														
Submission	P														
	A														