Topology Optimization of an Inter-Island Aircraft Rudder Quadrant Using Finite Element Method

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Abstract. Topology optimization has become an effective tool for mass reduction and good performance, especially in aeronautics and aerospace engineering. This research applies topology optimization using the finite element method (FEM) on the aircraft rudder quadrant structure of a 19 passengers inter-island aircraft. The analysis was performed by considering the maximum stress, mass reduction, and displacement that occur on the aircraft rudder quadrant in the initial and final design. In the initial design with a mass of 544.5 grams, the maximum stress and maximum displacement that occur is 24.4 MPa and 0.473 mm, respectively. In the final design, the mass reduction obtained is 13.77%, namely 469.5 grams, with a maximum stress of 22.6 MPa and maximum displacement of 0.579 mm. The static test results obtained after the redesign have decreased the maximum stress. This is because fillets can reduce the angular roughness between two surfaces, thereby increasing a more even stress distribution. It is expected that the implementation of the topology optimization on the quadrant component could comply with the required strength.

Keywords: Topology optimization, quadrant structure, finite element method, mass reduction

1. Introduction

Aircraft structural components are designed to achieve a balance between their weight and strength. Airplanes are known as engineering design products that use lightweight structures. A lightweight structure is a structure that is designed and built using lightweight and strong materials and utilizes advanced technology [1].

Topology Optimization is a powerful technique that has been applied in various fields, including the design of aircraft and aerospace structures [2]. Topology Optimization involves finding the optimal distribution of materials in a given design space. The goal is to minimize the weight of the structure while maintaining its strength and stiffness.

The use of Topology Optimization in aircraft design has been widely studied and applied in recent years. For example, a case study on topologically optimized design approach for additive manufacturing with lightweight design of jet engine bracket [3], [4] in this paper focuses on a

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topologically optimized design approach for additive manufacturing, the study results show that topology optimization is a powerful design technique to reduce product weight while maintaining design requirements if additive manufacturing is considered. In another study by P. D. Dunning et al [5], the internal structure of the wing box was optimized using the Topology Optimization method.

Case study by Aribowo et al, regarding a numerical study on topology optimization to design a lightweight and structurally strong composite fuselage frame on MALE UAV [6]. This research applies a numerical study of topology optimization of laminated composite structures using the finite element method (FEM), the results of the study show that the proposed topology optimization methodology is a promising approach for designing lightweight and structurally strong composite structures for MALE UAVs.

The case study by SHI et al [7] in this paper focuses on the combination of topology optimization and additive manufacturing technology, which can be used to design lightweight and high-performance structures. In this study, the authors designed a heavy-loaded aerospace bracket using topology optimization and manufactured it using additive manufacturing technology.

In this paper, we present a study on topology optimization of an inter-island aircraft rudder quadrant using finite element method. The Quadrant is an important control system component, especially for connecting the pilot control to the control surfaces. The Quadrant is located at the aircraft's rear and is actuated by the pilot through the rudder pedal. When the pilot presses the pedals or controls, the movement will be passed through the Quadrant to the mechanism that drives the rudder surfaces. This study aims to optimize the rudder quadrant design to improve its performance and reduce its weight.

2. Topology Optimization

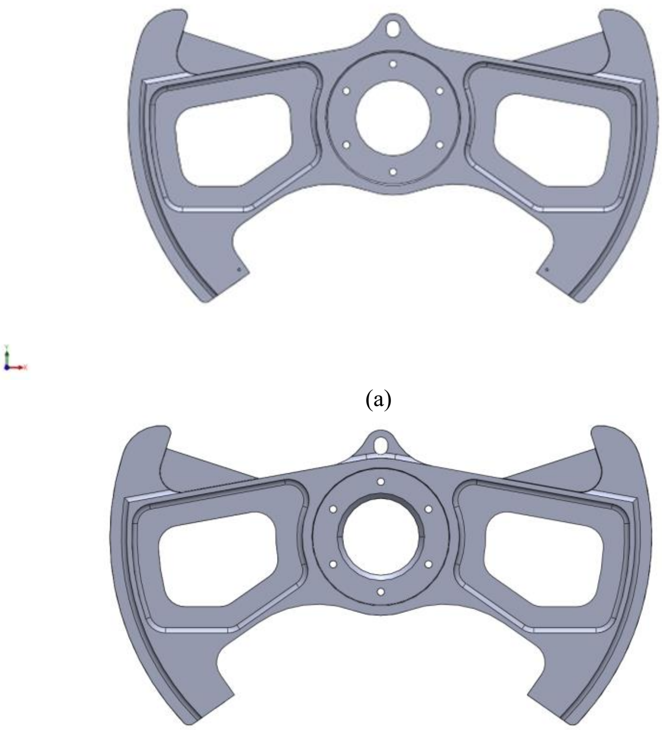
Design optimization is finding a design that meets certain criteria and satisfies design constraints. The requirements are called the objective function, and the design constraints are called the constraints. Examples of objective functions in design optimization are minimizing production cost or maximizing production efficiency. The general expression of design optimization can be shown in formula (1.1)[8], where x is the design variable (Quadrant), f(x) is the optimization objective (min compliance), g(x) is inequality constraints, and h(x) is equality constraints.

$$\begin{cases} \quad Minimize\ f(x) \\ Subjected\ to \begin{cases} g(x) \leq 0 \\ h(x) = 0 \end{cases} \end{cases} \tag{1.1}$$

3.Methods

3.1 Geometry Of Quadrant

Modeling is done in Solidworks software; the modeling can be seen in Figure 1. The first step is to import the Quadrant design from CAD software (Solidworks) into finite element software (MSC Nastran Patran). The next step is to define the type of material that will be used in the Quadrant part.



(a)

(b)

Fig.1. Quadrant part model Front (a) and back (b) view

3.2 Identification of Materials

In this study, the material determination of the Rudder Quadrant part using Aluminum Alloy 7050-T7451 material, the data obtained from the research is needed in the Rudder Quadrant design optimization. The data can be seen in Table 1 as follows.

Table 1. Aluminum Alloy 7050-T7451 Material Characteristic Data

No	Characteristic Data	Value
1	Modulus Elastisitas (E)	7096.7MPa
2	Poisson Ratio	0.33
3	Density	0.283 ^{3}

3.3 Research Procedures

The following is the sequence of procedures for conducting the Topology Optimization test, namely:

1) Literature study on topics related to this research.
2) Simulation of static tests using finite element software (MSC Nastran Patran).
3) Topology Optimization process.
4) Redesign by creating several designs using Solidwork software.
5) Final static simulation using software (MSC Nastran Patran) and determination of the optimal design.

3.4 Meshing Process

Meshing is the process of dividing geometry into small parts called mesh. The mesh has a specific shape and is interconnected between points/nodes [9]. In MSC Nastran Patran software, several mesh shapes can be used, namely, tetra, hex, and wedge. In this study, the mesh used is tetra mesh form with a global edge length value of 5; the mesh results can be seen in Fig 2.

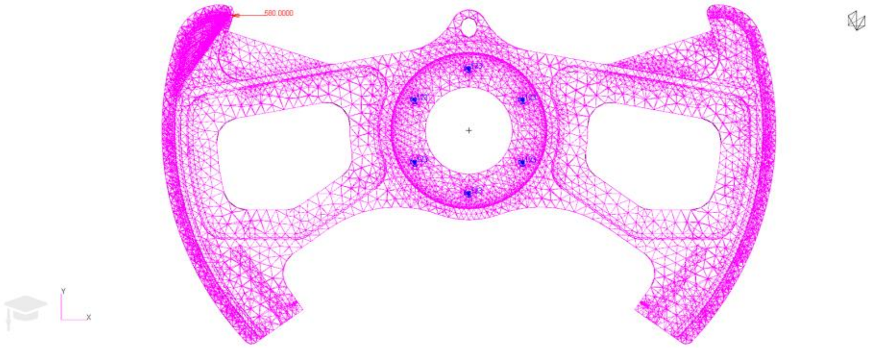
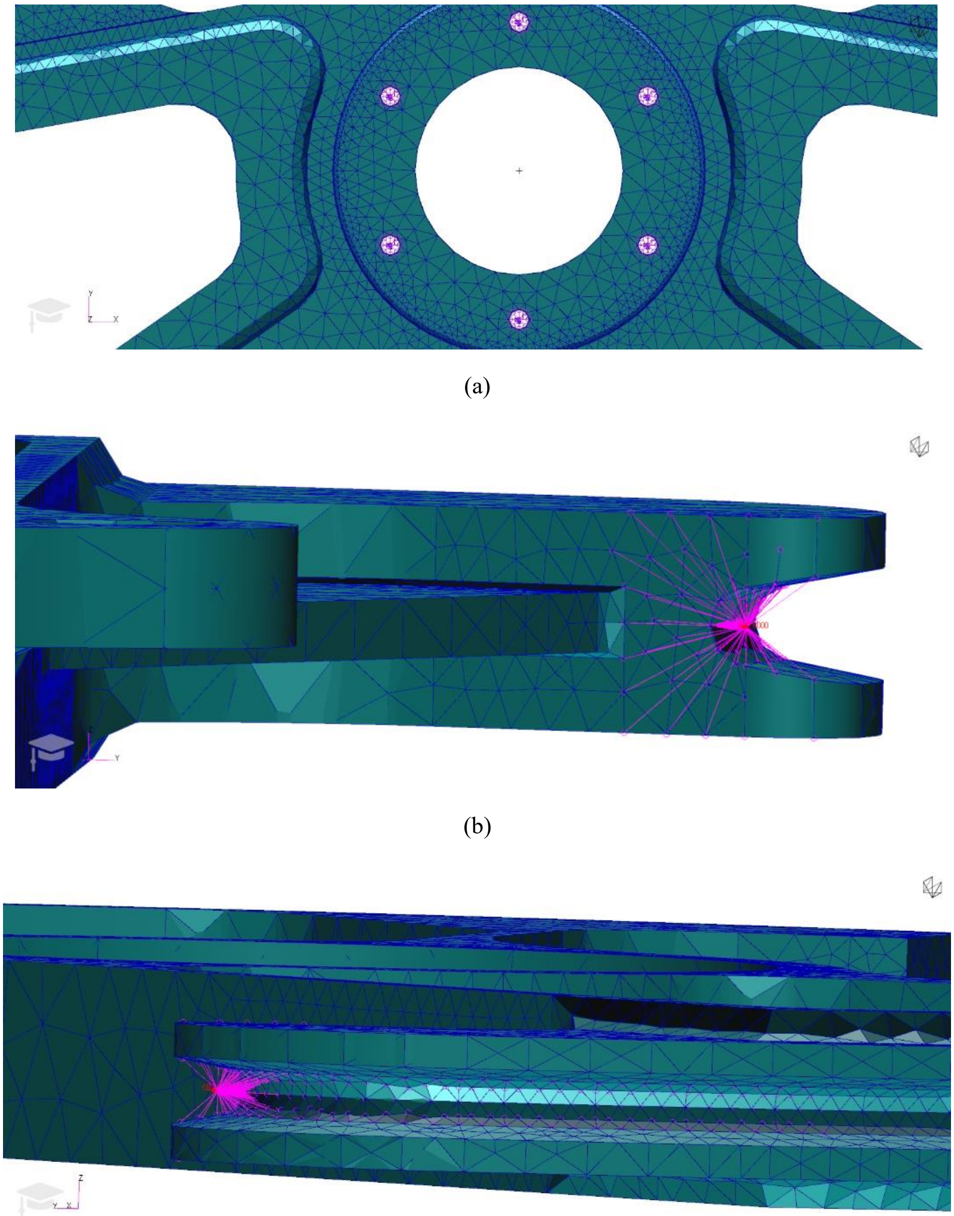


Fig.2. Meshing Result

3.5 Set Up Process

After the model is represented using finite elements through the meshing process, the next step is the process of selecting mpc using type RBE 2 on each bolt, which can be seen in Fig 3 a, and the force location can be seen in Fig 3 b and c.



(a)

(b)

(c)

Fig.3. Mpc Selection at each Bolt (a), Mpc Selection at Force Point (b), (c)

- **Location of Support Points**

  To obtain stress and deformation data, a fixed support is made, namely on each bolt, by inputting Displacement Constraint Translations (T1; 0, T2; 0, T3; 0) and Select Geometry Entities on each bolt, which can be seen in Fig 3.

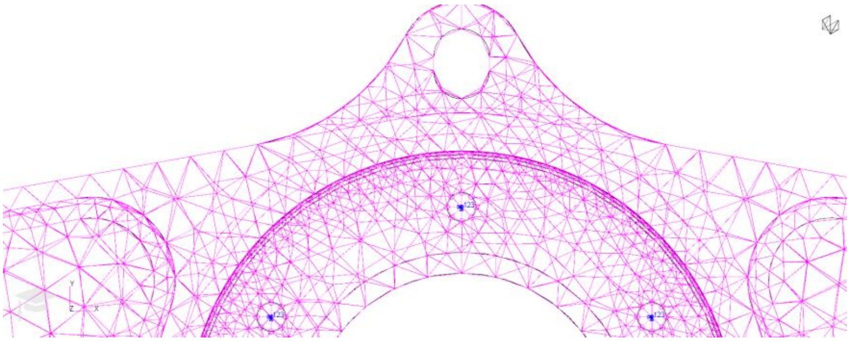


Fig.4. Input Displacement Constraint on Each Bolt

- **Load**

  In the part rudder quadrant, the loading was applied to the centre point of the cable by inputting a load of 580 N. The loading location can be seen in Fig 5. This loading aims to test the strength and stiffness of the part rudder quadrant.

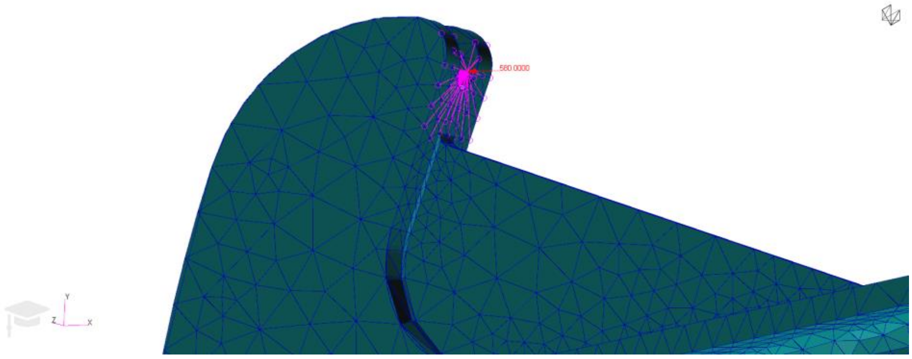


Fig.5. Input Load at the Center Point of the Cable

3.6 Optimization Process

The optimization method used in this research is topology optimization using MSC Nastran Patran software. The following are the steps to determine topology optimization:

- **Define the Design Domain**

  The selected part is usually called the domain design, the selection of the domain design must be based on the results of static tests to see parts that have low stress and margin of safety to see whether the part can be optimized. The following domain design on the Rudder Quadrant part can be seen in Fig 6.

Fig.6. Domain Design on Part Rudder Quadrant

- **Determine the Mass Target Constraint**
  Design constraints refer to limitations or restrictions in the design process that are tied to the response to ensure that the optimization results are acceptable [10]. In this research, the target constraint is in the form of a mass fraction with a target mass of 20%

4. Results and Discussion

4.1 Static Simulation Results Before Topology Optimization

Static analysis is performed to determine whether the material used can meet the design requirements. This analysis produces stress and displacement values from the design. The maximum stress value generated is 24.4MPa, and the maximum displacement value generated is 0.473 mm. The static analysis results can be seen in Fig 7 and Fig 8.

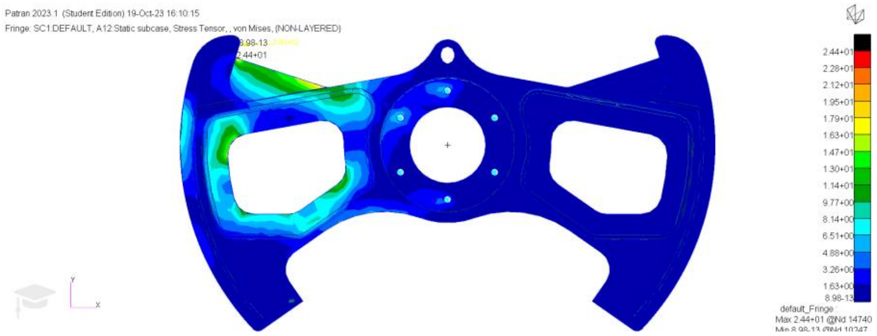


Fig.7. Max Stress Value of Rudder Quadrant Part

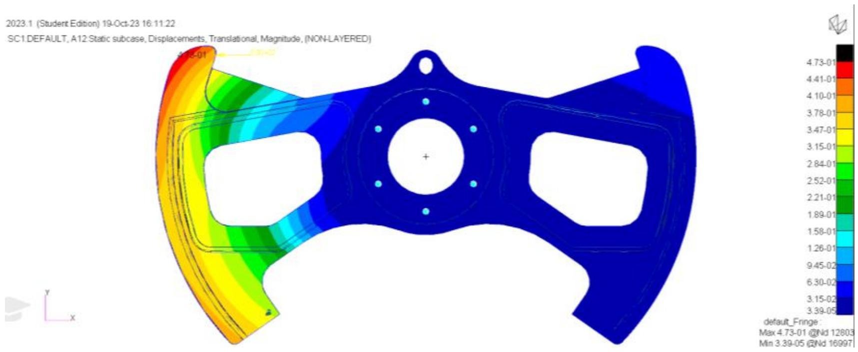


Fig.8. Max Displacement Value of Rudder Quadrant Part

4.2 Topology Optimization Result

The optimization results are illustrated in Fig 9, where the material is removed from the part that is not really affected by the applied force so that a lighter rudder quadrant is obtained with the resulting mass reduction to 483.3 grams with an initial mass of 544.5 grams or a mass reduction of 11.23%.

Fig.9. Topology Optimization Result

4.3 Static Simulation Results After Topology Optimization

The results of static analysis after Topology Optimization can be seen in Fig 10 and Fig 11. Based on the static simulation results, the Max stress value generated is 25.3 MPa, and the Max Displacement is 0.479 mm.

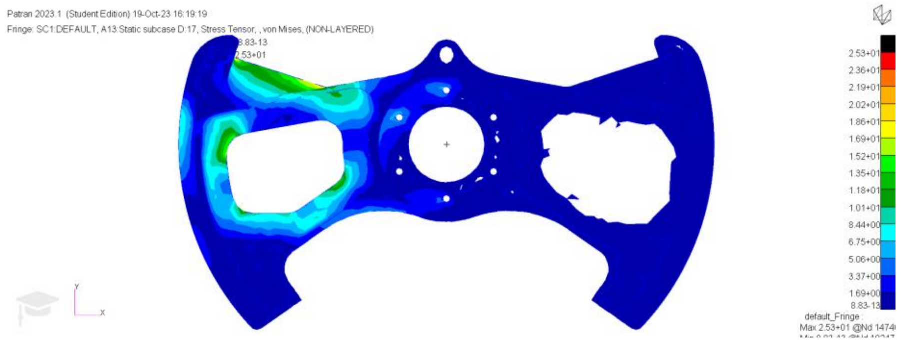


Fig.10. Max Stress Value of Rudder Quadrant Part After Topology Optimization

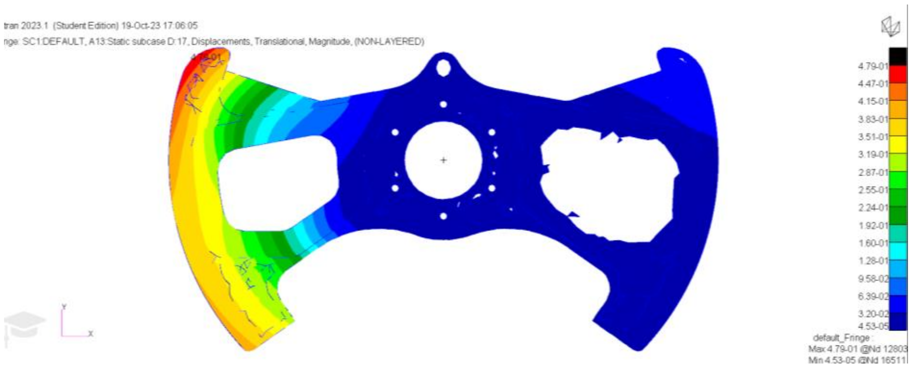


Fig.11. Max Displacement Value of Rudder Quadrant Part After Topology Optimization

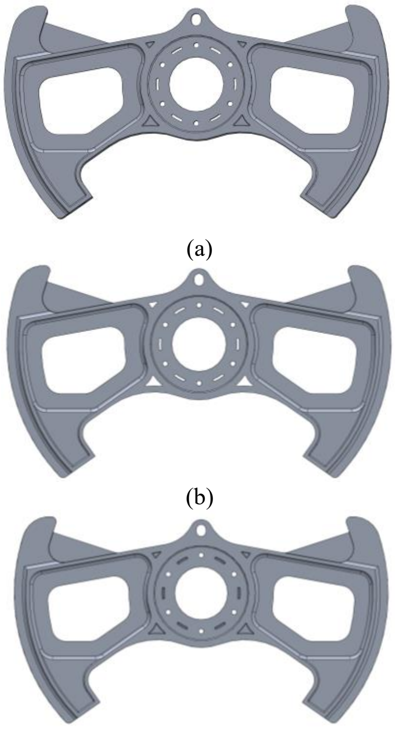
4.4 Redesign Results and Static Test Results

Redesign Results

Based on the results of the rudder quadrant redesign topology optimization using Solidwork CAD software, it has resulted in a significant decrease in mass, as shown in Table 2 and Fig 12 (a), (b), (c) and Fig 13 (a), (b), (c)

Table 2. Comparison of Initial Design Results with design after topology optimization

No	Initial Mass (g)	Mass After Topology Optimization (g)	Change%
1	544.5	515.7	-5.28
2	544.5	510.1	-6.31
3	544.5	519.7	-4.55
4	544.5	501.8	-7.84
5	544.5	507	-6.88
6	544.5	469.5	-13.77

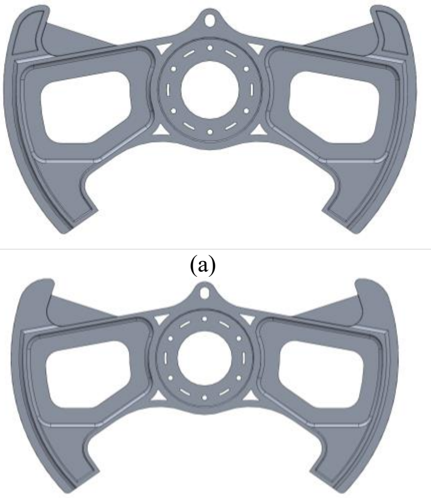


(a)

(b)

(c)

Fig.12. Redesign Results Using Solidwork Software (a), (b), (c)



(a)

(b)

(c)

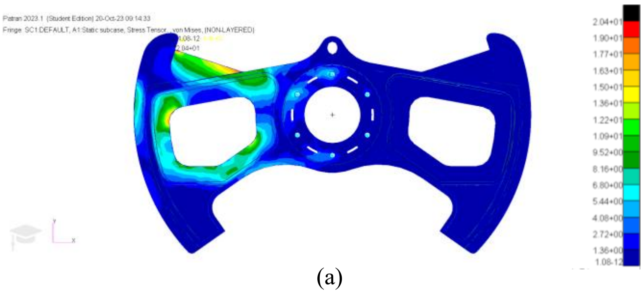
Fig.13. Redesign Results Using Solidwork Software (a), (b), (c)

Stress results on the Static Test

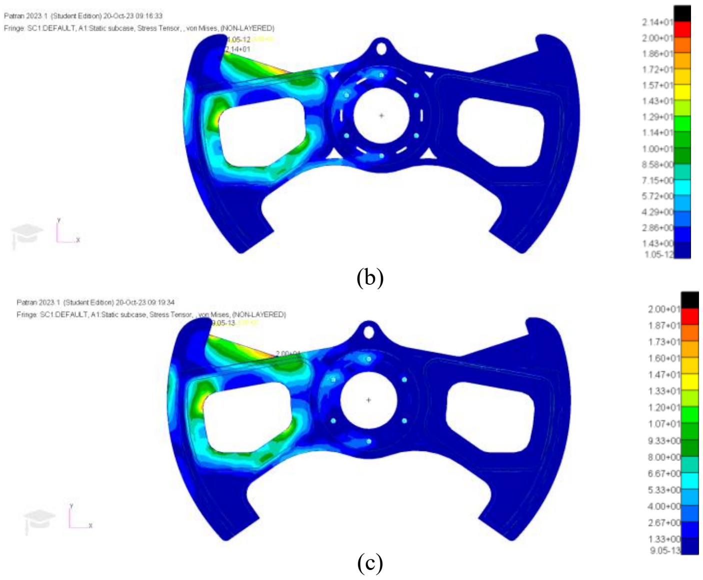
The results of the static test in this study using MSC Nastran Patran software obtained the results of the static test after the redesign decreased the maximum stress, and the use of fillets in the redesign in Solidwork software can reduce the maximum stress. This is because fillets can reduce the angular roughness between two surfaces, increasing an evener stress distribution. As shown in Table 3 Comparison of Initial Maximum Stress and Maximum Stress After Optimization can be seen in Figure 14 (a), (b), (c), (d), and Fig 15 (a), (b), (c), (d) Maximum Stress rudder quadrant values of parts.

Table 3. Comparison of Max Stress Initial and Max Stress After Optimization

No	Initial Maximum Stress (Mpa)	Final Maximum Stress (Mpa)	Change%
1	24.4	20.4	-16.39
2	24.4	21.4	-12.30
3	24.4	20	-18.03
4	24.4	19.9	-18.44
5	24.4	19.8	-18.85
6	24.4	22.6	-7.37



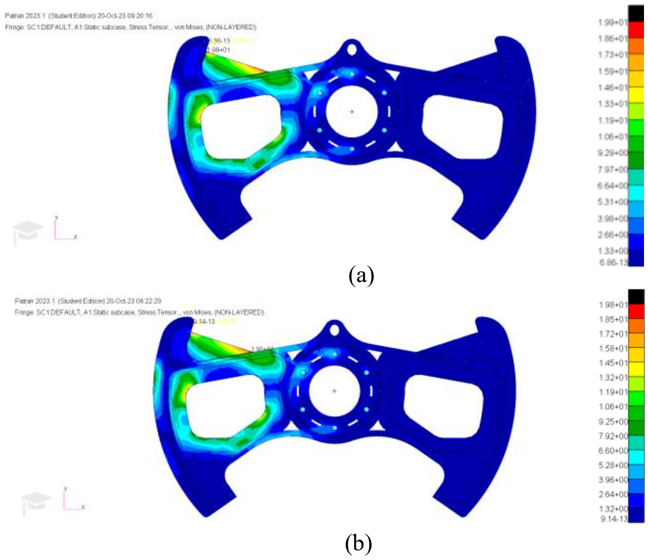
(a)



(b)

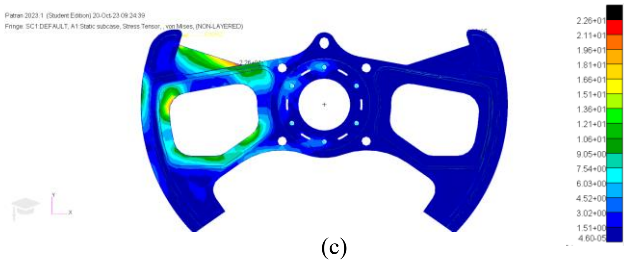
(c)

Fig.14. Max Stress part Rudder Quadrant value (a), (b), (c)



(a)

(b)



(c)

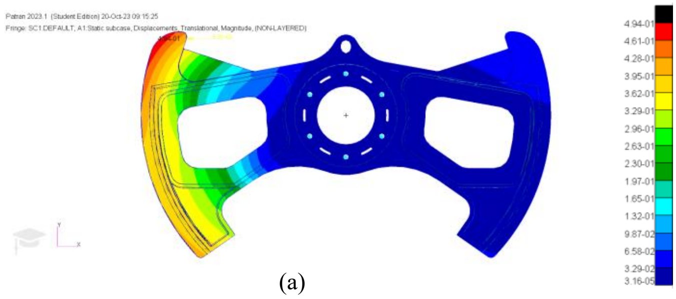
Fig.15. Max Stress part Rudder Quadrant value (a), (b), (c)

Displacement Static Test Results

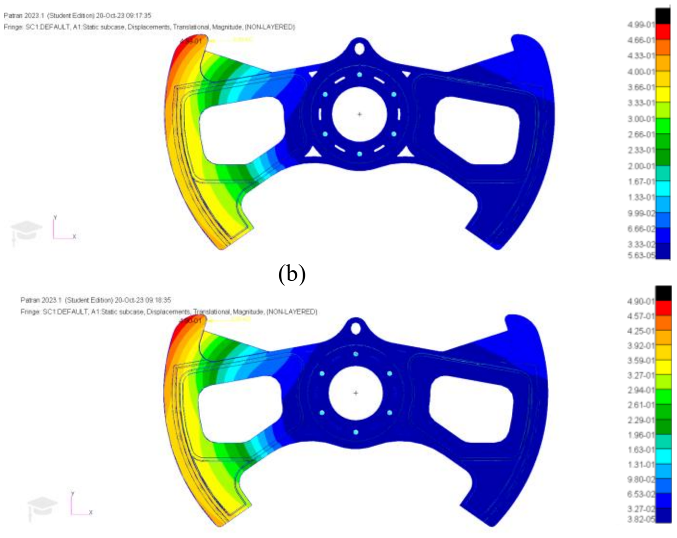
The results of the static test in this study found that the results of the static test after the redesign experienced an increase in maximum displacement, as shown in Table 4. Comparison of Max Displacement Initial and Max Displacement After optimization, can be seen in Fig 16 (a), (b), (c) and Fig 17 (a), (b), (c) Max Displacement Value Part rudder quadrant.

Table 4. Comparison of Max Displacement Initial and Max Displacement After Optimization

No	Initial Maximum Displacement (Mpa)	Final Maximum Displacement (mm)	Change%
1	0.473	0.494	+4.44
2	0.473	0.499	+5.50
3	0.473	0.49	+3.59
4	0.473	0.506	+6.98
5	0.473	0.505	+6.77
6	0.473	0.579	+22.4



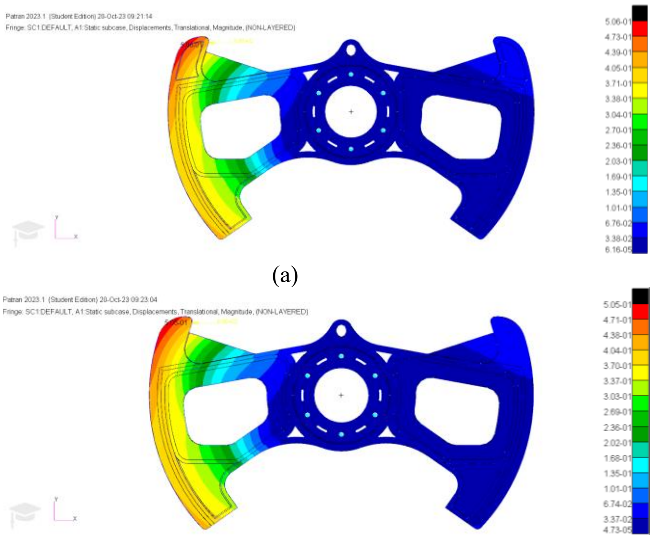
(a)



(b)

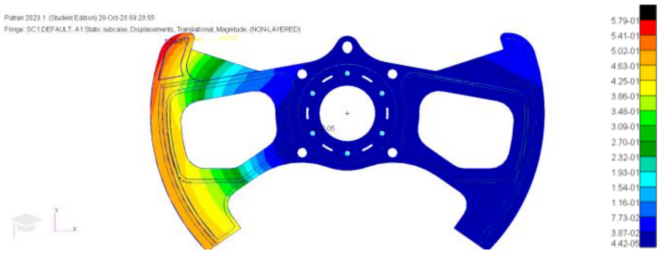
(c)

Fig.16. Part Rudder Quadrant Max Displacement Value (a), (b), (c)



(a)

(b)



(c)

Fig.17. Part Rudder Quadrant Max Displacement Value (a), (b), (c)

4.5 Discussion of Topology Optimization Results

Topology optimization is a structural optimization method that aims to minimize mass and volume by using a stress distribution approach [11]. This research uses topology optimization to create a lighter rudder quadrant design. This can be seen by comparing the initial design and the design after optimization in Table 5. Fig 18 shows the initial design, while Fig 19 shows the results of redesign 6, the design after optimization.

Table 5. Comparison of initial design with design after optimization

Properties	Initial Design	Optimised	Percentage (%)
Mass (g)	544.5	469.5	-13.77%
Maximum Stress (MPa)	24.4	22.6	-7.37%
Maximum Displacement (mm)	0.473	0.579	+22.4%

Fig.18. Quadrrant Rudder Initial Design

Fig.19. Rudder Quadrant Design After Optimization

5. Conclusions

Based on the results of the research conducted, it can be concluded that the results of redesign 6 are the most optimal results based on test simulations using the finite element method in MSC Nastran Patran software. The final mass obtained after Topology Optimization is 469.5 grams, with an initial mass of 544.5 grams or a mass decrease of 13.77%. Max stress decreased by 22.6 MPa, and Max displacement after Topology Optimization increased by 0.579 mm. The use of fillets can result in a decrease in maximum stress because fillets can reduce the roughness of the angle between two surfaces. A sharp angle will cause stress concentration so that the stress will be concentrated in that area. This can cause damage to the material if the stress exceeds its strength limit. Fillets can reduce stress concentration by making the corners smoother. Thus, the stress distribution will become more even, and the maximum stress will be reduced.

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