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Structural Optimization and Weight Reduction of Spar and Ribs

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***Abstract*— The main objective of this project is to optimize and reduce the weight of Spar and ribs of the wing. And in order to achieve the structure as light as possible for the same loading conditions and boundary conditions. This paper mainly concentrated on optimization of spar and ribs. The Software employed for this work are CATIA v5 for modeling of ribs and spar, Altair hypermesh for meshing, MSC NASTRAN for displacement and stress analysis of spar and ribs of wing and optistruct is used for the optimization process. Airfoil selection and analysis is done using XFLR 5. Composite materials are employed for this work. The results of Displacement and stress analysis are analyzed from the MSC NASTRAN. Topology optimization is carried out by using optistruct. The volume fraction is the objective function and displacement as a design constraint. The work is aimed to reduce the weight of the structure to 10%. And at the same time, the mass of the structure is reduced.**

Keywords*— *Topology Optimization; Composite Material; Finite Element Analysis.

NOMENCLATURE

b	Span in m
ρ	Density in ton\m³
S	Wing Surface Area in m²
W/S	Cruise Wing Loading in N\m²
Vcruise	Cruise Velocity in m\s
c_l	Lift coefficient
W	Weight in kg or N
c_r	Chord Root in m
C_t	Chord tip in m
g	Acceleration due to gravity
$V_{Initial}$	Volume of structure the before optimization
V_{Final}	Optimized volume of structure
$W_{Initial}$	Weight of the structure before optimization
W_{Final}	Weight of the structure after optimization
MAC	Mean Aerodynamic chord
L^T (y)	Total lift generated by wing with trapezoidal plan form
FE	Finite Element

I. INTRODUCTION

Optimization [1] is achieving the maxima or minima in the structure. Aviation industry is having the great advantage of the optimization process. In this paper, optimization is carried out to reduce the weight of the structure. This work is based on reducing the weight of the structure so that the structure can carry the payload under the same loading conditions and a number of iterations are carried out in the optimization process. Composite materials [7] are employed for this work. Selected materials are CFRP, GFRP, and Balsawood. CFRP is for the spar, GFRP is for the wing skin and balsawood for the ribs. Theoretical design of the wing is carried out by considering the standard values. The geometry of the wing spar and ribs are designed using the CATIA V5 and FE model[8] is done with Altair hypermesh. Spar is the main structural member which carries a bending load. Single spar is employed for this thesis. Ribs are the structures of the wing, which gives the shape to the wing. Stress and displacement analysis are carried out in this work. Topology optimization is carried out by taking the displacement as a design constraint. The material can be removed or thickness of the structure is reduced by the process of optimization.

II. METHODOLOGY

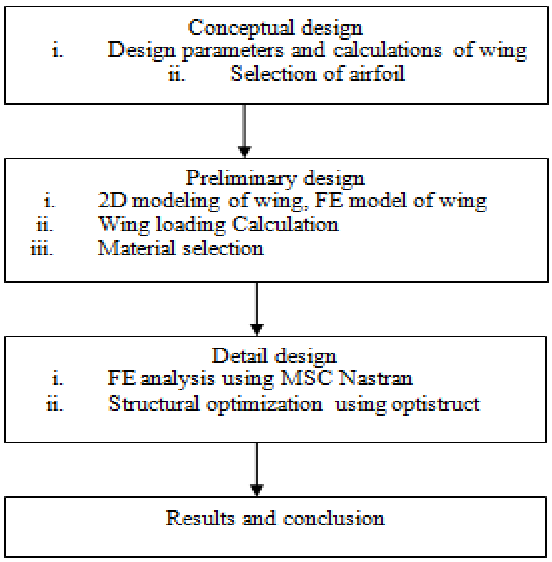

Fig 1: Design methodology followed for entire work

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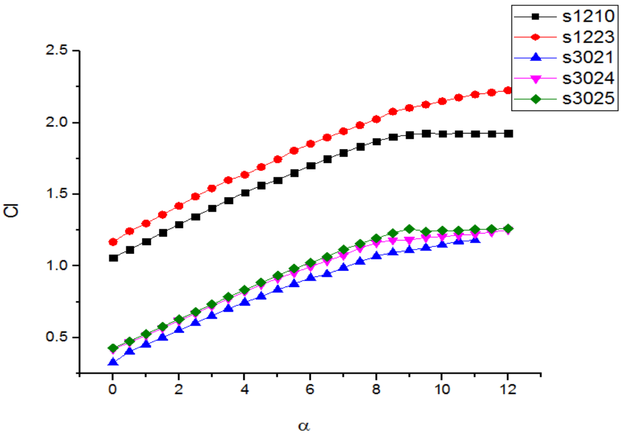
A. MODELING OF WING

1) Aerofoil Selection

Aerofoil selection is main important criteria for wing design. Aerofoil selected should meet all the requirements such as good aerodynamic performance, lower stall velocity, high lift etc. The airfoils selected are a low-Reynolds number (Re) with high lift.

Compared to NACA airfoil, Selig airfoil is having a high camber and also high Cl value; therefore Airfoils selected are Selig airfoils with high camber.



Graph 1: Comparison of the angle of attack Vs coefficient of lift

Selected airfoils are

- S1210 12%
- S1223
- S3021
- S3024 9.84%
- S3025 9.38%

By observing the graph1 with a different airfoil, S1223 is having a high Cl value but at the same time drag is inaccured at that lift. But in case of S1210 Cl is nearly 2 and it stalls at a particular value of the angle of attack and Cl is drastically changing at the particular angle of attack.S1210 having a high slope. Therefore by considering above parameters, Airfoil S1210 is selected.

2) Wing Modelling

Data requirements for the design of the wing

- Wing loading
- Aspect ratio
- Wing span
- Wing area
- Taper ratio
- Root chord
- Tip chord
- MAC

The density of the air at the required altitude is selected from the standard atmospheric graph which is altitude (Km) versus temperature (K). The selected density is at cruise condition that is 2500m above the sea level. The density at this altitude is 0.957 kg/m³.

Table 1: Available parameters for the design of the wing

Give n	Value	Units
Weight	68.67	N
Vstall	10	m/s
Vcruise	15	m/s
CLmax	1.92	-
Cruise Altitude	2500	m
Altitude Sea Level	0	m
g	9.80665	m/s^2
Density sea level	1.225	kg/m^3
Density cruise alt	0.9750	kg/m^3

3) Wing load calculation

L= ($\rho V^2 S Cl$)/2 mm

A load of 68.67N when calculated for from the lift formula and the pressure is calculated as 2.14 x 10^{-4} N/mm². This pressure is applied as uniformly on the spar.

a) Span wise load distribution

The wing plan form is trapezoidal, required parameters for calculation of UVL are 863mm semi-span of the wing and lift force
68.67N.

Table 2: Analytic span wise lift distribution is

Y/(b/2)(m)	L^T (y) N/mm
0	0.045888
0.17381	0.043767
0.34762	0.041645
0.51332	0.039622
0.6755	0.037642
0.83777	0.035662

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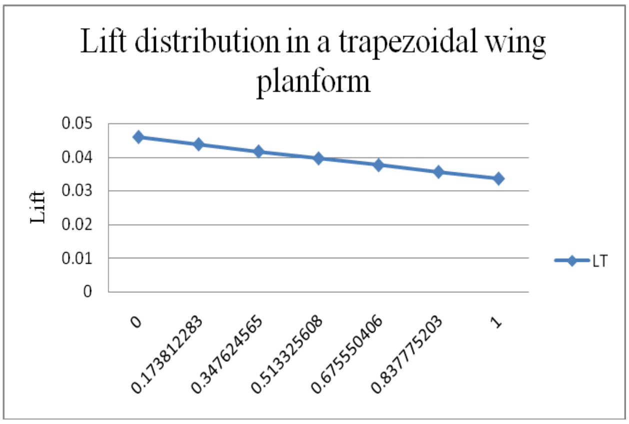

Graph 2: Lift distribution in trapezoidal wing

4) Material selection

The material selection is an important criterion in the aircraft structure [7]. The material used is CFRP for the spar, balsa wood for the ribs and GFRP for the skin.

Table 3: Material proprieties

Materials	Young's modulus (Mpa)	Poisson's ratio(μ)	Density ρ (ton/mm³)
CFRP	4.5×10^{4}	0.2	1.6×10^{-9}
GFRP	1.8×10^{4}	0.162	1.7×10^{-9}
Balsa wood	3×10^{3}	0.3	8.3×10^{-9}

B. CATIA AND FE MODEL OF WING RIBS AND SPAR

1) Modeled wing in catia

After the theoretical calculation of the wing, export the airfoil coordinates from the MS Excel to the CATIA and created the airfoils. Scale it to the required dimension of the wing tip and wing root. Create a surface for the wing as shown in fig. next is to export the wing surface model to the hypermesh to create the mesh.

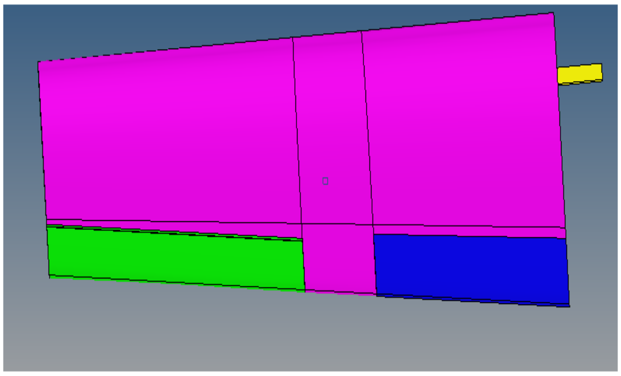

Fig 2: Modeled wing in catia

2) FE model of wing

Import the CATIA model [8] of the wing surface to the hypermesh to carry out the meshing. Spar and ribs in the wing are created using hypermesh with meshing. For the skin, spars and ribs are meshed with the 2D meshing.

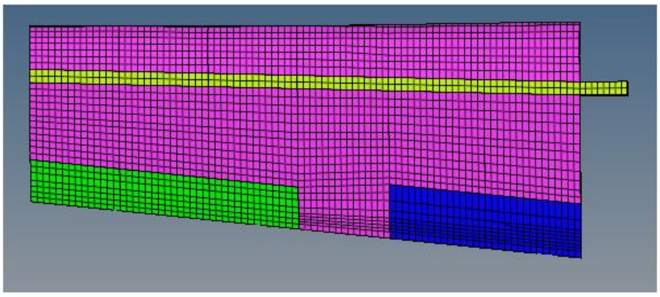

Fig 3: FE model of wing

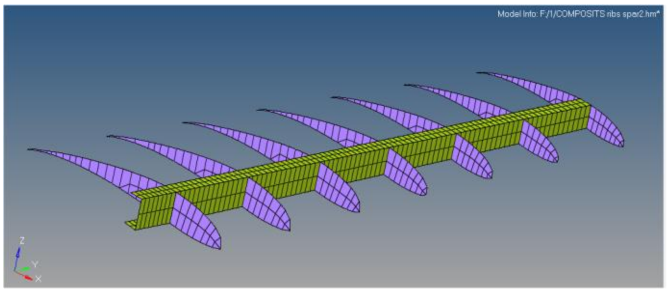

Fig 4: FE model of ribs and spar

C. ANALYSIS OF STRUCTURE

a. Normal mode analysis

Dynamic load is one in which it changes with time fairly quickly in comparison to structural natural frequency. The modal analysis determines the mode shapes (vibration shapes) and frequencies [2] for the particular mode shape of a structure for free vibration analysis.

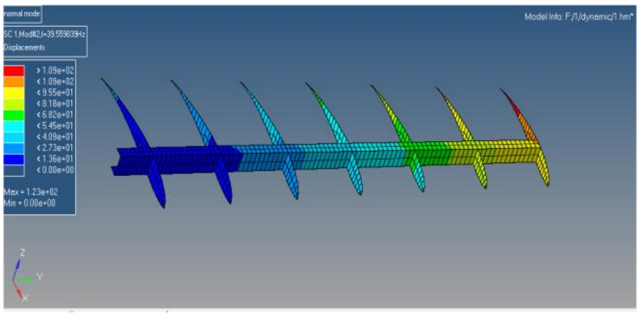
Fig 5: Mode 1

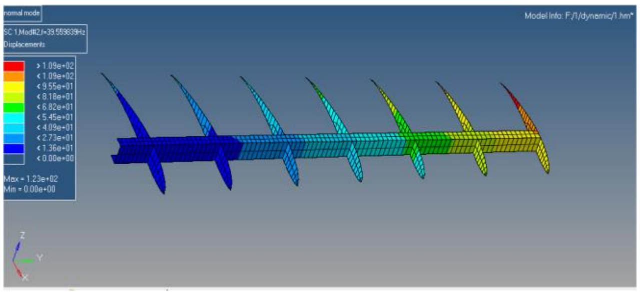
Fig 6: Mode 2

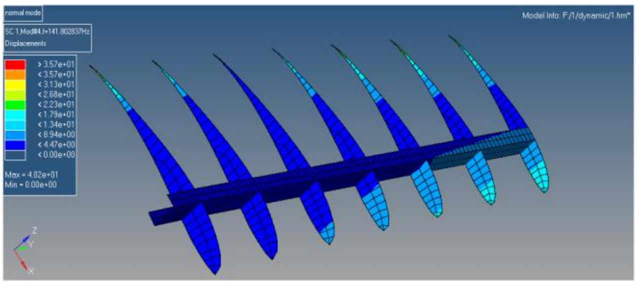
Fig 7: Mode 3

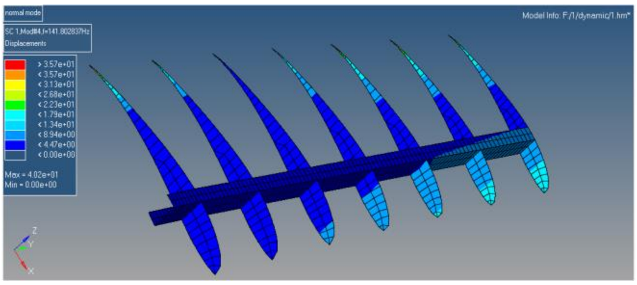
Fig 8: Mode 4

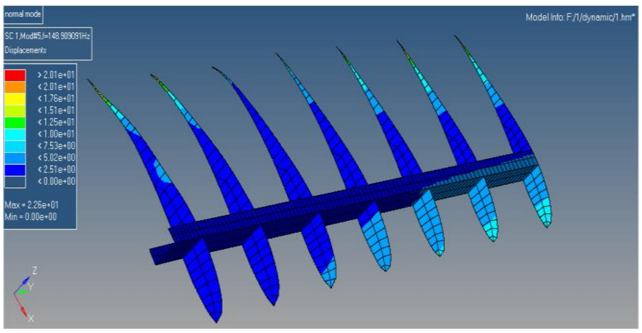
Fig 9: Mode 5

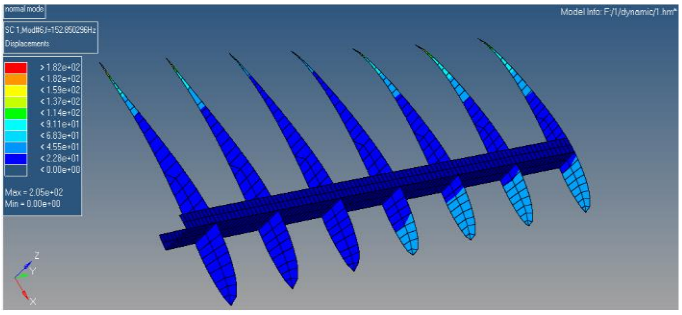
Fig 10: Mode 6

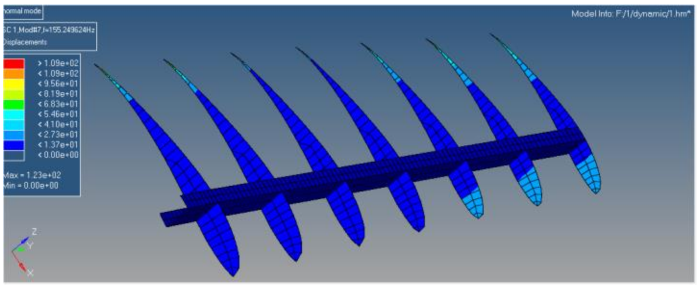
Fig 11: Mode 7

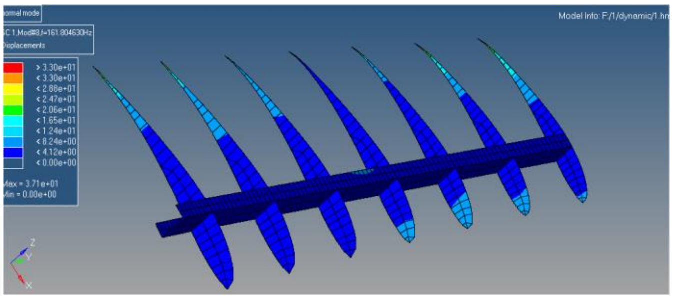
Fig 12: Mode 8

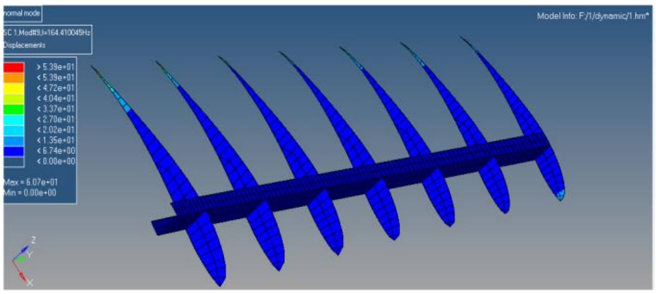
Fig 13: Mode 9

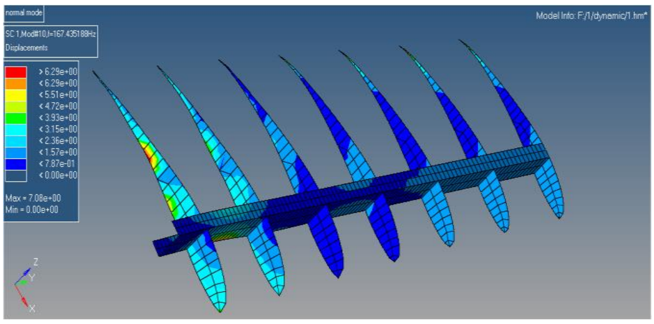
Fig 14: Mode 10

b. Static analysis

In this thesis bending load is employed to carry out the analysis. The uniformly distributed load is applied on the wing surface. In this work, Maximum von misses stress displacement in the model will be studied.

The analytical values of stress and displacement are, for the UDL stress is 0.14 N/mm² and displacement is 0.22mm, for the UVL, stress 0.18 N/mm² and displacement is 0.16mm.

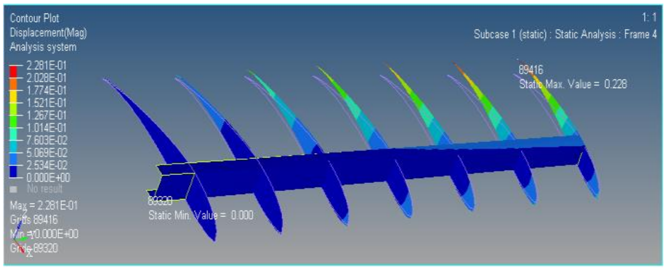

Fig 15: Displacement in the spar with ribs for UDL

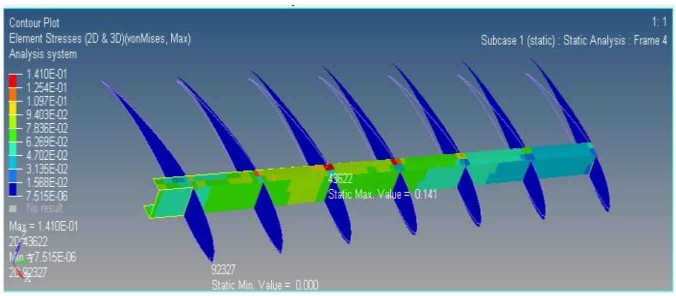

Fig 16: Stress in the spar and ribs for UDL

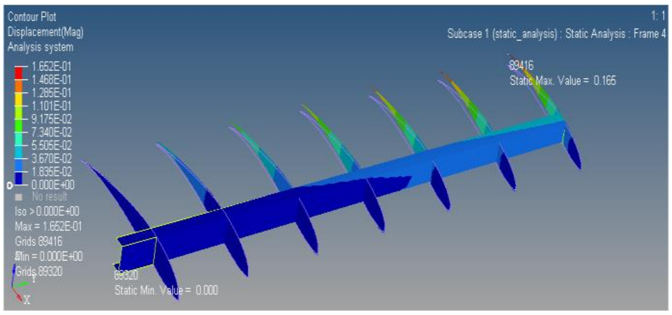

Fig 17: Displacement in spar and ribs for UVL

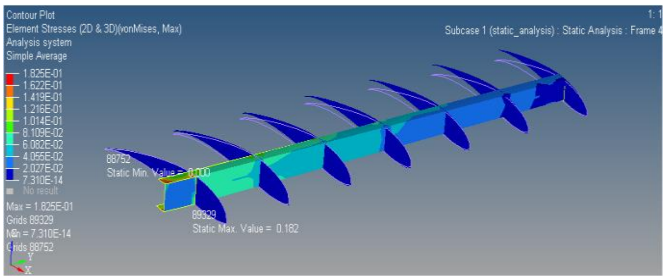

Fig 18: Stress in spar and ribs for UVL

c. Optimization of the wing structure

Optimization [3][4][5], is finding the maxima and minima in the structure. Optimization of the geometry parameter works well at the individual component level rather than complicated assemblies.

i. Topology optimization

The objective of topology optimization is to reduce the weight of the structure by removing material in the in the structure where the stress is very high or load acting on the structure is less or the place where the structure experiencing the less force.

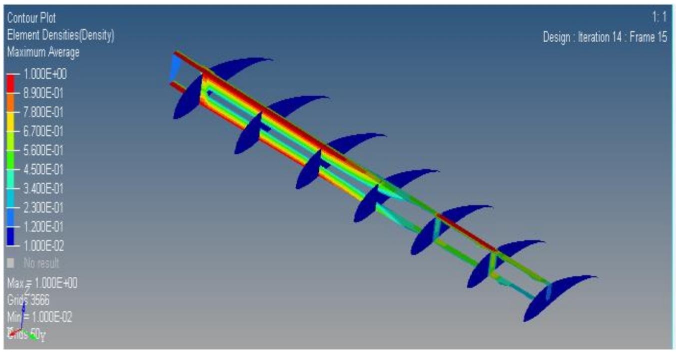

Fig 19: Optimized spar for UDL

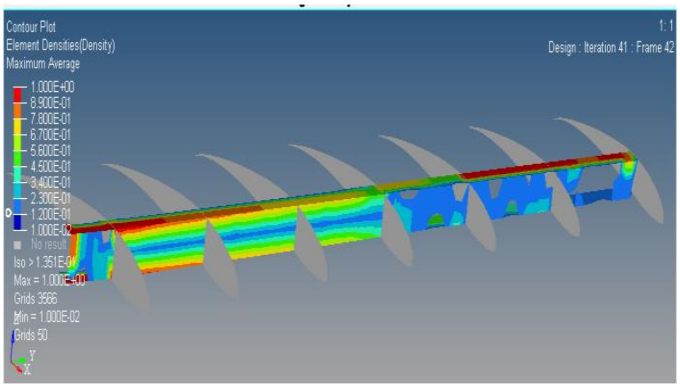

Fig 20: Optimized spar for UVL

Table4: Optimized results

Parameters	UDL	UVL
Initial volume	109741	109741
Initial mass	1.745×10^{-4}	1.613×10^{-4}
Final volume	99042	104969
Final mass	4.589×10^{-5}	1.8126×10^{-5}
Volume reduction in %	9.75	5
Mass reduction in %	26.3	11

CONCLUSION

This work is carried out for the existing wing ribs and spar. It is mainly concentrated on spar and ribs of the wing. The normal mode analysis is done with the different frequency and static analysis is done by applying the structural load on the wing skin. The iterative analysis was carried out to achieve minimum weight for the structure using optistruct. . Work met with the objective that the result showed spar is cut out like structure and a weight reduction of 10%. Amount of material in the rib is removed by reducing the thickness of the ribs. Demonstrate that the TO is an effective and rational design tool for the design of continuum structure, especially aircraft structures.

SCOPE OF FUTURE WORK

The optimization process is developing day by day because of high advantages to the aviation industry. Optimization process will reduce the cost of the material by removing the amount of material to be used. And from this method, lightweight structure can be achieved. In this work, the weight of the structure can be reduced by using less thickness for the structural components. We can have a better more smoothly surface of the structure by implemented topology optimization method. In this future work, experimental work is needed to examine the thesis work.

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