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Structural Design &Optimization of an Unmanned Aerial Vehicle Wing for SAE Aero Design Challenge

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ABSTRACT

Aircraft design is a multi-disciplinary iterative design process which follows a Systems Engineering approach and Unmanned Aerial Vehicle design follows one such design methodology. This paper is an attempt to formulate the structural design process for a UAVwing and subsequent optimizationfor SAE India Aero Design Challenge 2017.The design starts with the identification of structural design parameters and challenge requirements in the Pre-design/Conceptual Design phase. Based on the engineering values, a mathematical interface is coded in MATLAB to calculate the mechanical equivalents for the wing at individual sections and to prepare an internal structural layout adhering to the selected material properties. The structural design of the wing is then modelled in Solidworks and final mass is calculated in the Preliminary Design phase. For initial estimates, the static structural analysis of the layout is performed theoretically.The final design of the wing is then fed in ANSYS Finite Element Solver for Static Structural analysis. Now, successive iterations are performed for the optimization of a critical structural parameter with bound constraints directly affecting the mass of the structure using MATLAB in the Detailed Design phase. The optimized version is then finally validated.

Keywords: *UAV; Structural Design; Optimization; MATLAB.*

1.0 Introduction

SAE Aero Design Challenge 2017 is a UAV design challenge to be held in March 2017 in India. The competition aims at maximizing the payload carrying capacity of the UAV while completing a full circuit of the airfield. The constraint of maximizing the payload of the UAV directly influences the engineering design of the wing of the UAV since wings prove to be an important subsystem which provide both aerodynamic worth and structural integrity to the UAV. It therefore calls for the design and analysis of wings carefully engineered so as to cater to the requirements of the challenge.An attempt has been made through this research, to comply by the requirements as close as possible while reaching towards an optimized version of the wing. Any research work is never complete since there is always a scope for better solutions as we progress and touch newer domains.The focus of this research is limited to the structural design and optimization of the wing of the unmanned aerial vehicle only, although, other subsystems of the UAV were designed and developed too. Following is the design methodology developed for this research work.

2.0 Conceptual Design Phase

The design process of the wing starts with the identification of critical structural design inputs that are derived from the set of competition requirements which are fed into MATLAB for further mathematical modelling.

2.1 Structural design inputs

The structural design inputs were derived by identifying the most influential parameter from the set of design parameters for the competition. The payload capacity proved to be the most influential

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parameter and was taken as the basis for further design of the wing.

The corresponding starting value for the influential parameter was taken as 5g ie. the designed wings should be able to sustain 5 times its own weight without structural failure. The other structural parameters like exposed wing area, root chord and tip chord were calculated during the aircraft design and have not been included in this research. The design factor of 1.5 has been taken for maximum reliability of around 99%. The wing airfoil for the aircraft was taken as Selig 1210.

3.0 Preliminary Design Phase

The preliminary design phase starts with mathematical modelling of the structural design in MATLAB. The design method adopted has been displayed in a flowchart in figure 2.

3.2 Structural sizing

The developed mathematical model is now run in MATLABas a live script. The code initiates with a prompt command where it asks the user to enter 13 values and the code then calculates the rest of the variables as described in the flowchart.

After dividing the wing into number of divisions, the location of center of pressure is taken as well as the position of the front spar and the rear spar.

Center of Pressure= 45% of chord length from the leading edge

Front spar position= 25% of chord length

Rear spar position = 62% of chord length

Further sizing of the wing components were done keeping into consideration the maximum values of shear force and bending moment distribution on the spars.

Maximum Bending moment=78384 N-mm

Maximum shear force = 85.1575 N

Material for front spar= AA 6061 T-6

Material for rear spar= Birchwood

Volume of front spar = 45555 mm^3

Volume of rear spar= 67767 mm^3

Total volume= 113322 mm^3

Total mass of the spars= 316.1701 gms

3.3 Performance charts

After the mathematical model displayed and stored the mechanical values for the wing, performance charts were plotted on MATLAB for variables as a function of the chord length at each section from tip to root for both the front and rear spars. The following plot shows the variation of shear force due to torsion and the total shear force as a function of chord length.

3.4 Initial blueprint

The obtained wing design from the mathematical model is then modelled in Solidworks for further analysis in the detailed design phase.

Fig 1: Design Methodology

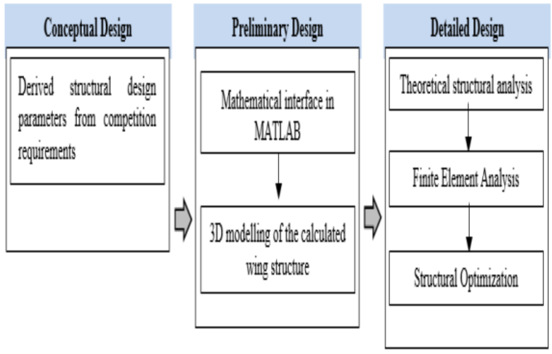


Table 1: Competition Requirements

S.No	Design Parameter	Objective
1.	Time Limit	< 180 sec
2.	Take-off distance	< 400 feet
3.	Landing Distance	< 400 feet
4.	GTOW (excluding payload)	< 5 kgs
5.	Payload	**Maximise**

Table 2: Derived Structural Parameters

S.No	Structural Parameter	Value/Range
1.	Root chord/Tip Chord	380/230 mm
2.	Exposed span	2000 mm
3.	Aircraft weight	<= 50N
4.	Lift Load	5g
5.	Design Factor	1.5
6.	Exposed wing area	726000 mm^2

Fig 2: Mathematical Modelling Flowchart

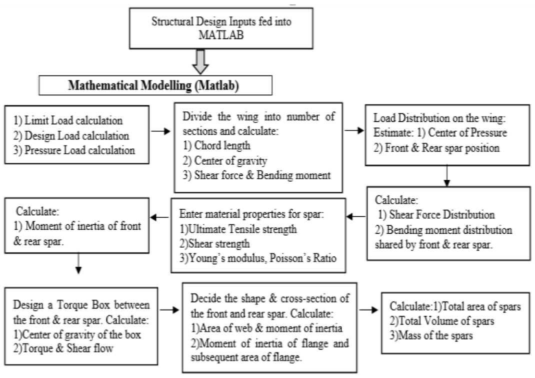


Fig 3: User I/O Live Script in MATLAB to Input Design Parameters

```
prompt1= 'What is the root chord of your plane in mm?';
Root_chord=input(prompt1)                                  Root_chord = 380

prompt2= 'What is the tip chord of your plane in mm?';
Tip_chord=input(prompt2)                                   Tip_chord = 230

prompt3= 'What is the semi-span length of your wing in mm?';
Semispan_length=input(prompt3)                             Semispan_length = 1127
```

Fig 4: Chord Length Calculations by Dividing the Wing into Number of Sections

```
%% Chord Length calculation %%
L(1)=230;
for i=2:11
    L(i)=Root_chord - ((Root_chord-L(1))/Exposed_span)*(Exposed_span-((i-1)*(h)))
end
```

Fig 5: Cumulative Shear Force Calculation

```
%% Cumulative Shear Force at each section %%

P_matrix=[P(1) P(2) P(3) P(4) P(5) P(6) P(7) P(8) P(9) P(10)];
csf=cumsum(P_matrix)
```

Fig 6: Bending Moment Calculation

```
BM_at_tip=0;
BM(1)=P(1)*CG(1);
BM(2)=P(1)*CG(1)+P(2)*CG(2)+P(1)*h;
BM(3)=P(1)*CG(1)+P(2)*CG(2)+P(3)*CG(3)+2*P(1)*h+P(2)*h;
BM(4)=P(1)*CG(1)+P(2)*CG(2)+P(3)*CG(3)+P(4)*CG(4)+3*P(1)*h+2*P(2)*h+P(3)*h;
```

Table 3: Shear Force & Bending Moment Distribution on the Front and Rear Spar

Sections on the wing (mm)	Chord length at each section (mm)	Shear Force on front spar (N)	Bending Moment on front spar (N-mm)	Shear Force on rear spar (N)	Bending Moment on rear spar (N-mm)
TIP-1127	230	-	-	-	-
S1-1014.3	245	5.6364	569	6.6311	671
S2-901.6	260	11.6289	2300	13.6810	2711
S3-788.9	275	17.9773	5263	21.1498	6204
S4-676.2	290	24.6817	9531	29.0373	11234
S5-563.5	305	31.7421	15174	37.3436	17884
S6-450.8	320	39.1585	22262	46.0688	26240
S7-338.1	335	46.9308	30869	55.2128	36383
S8-225.4	350	55.0592	41063	64.7755	48399
S9	*Table 4. Moment of inertia of spars; Torque box design, cumulative torque and shear flow on wing*				
ROOT-0	380	72.3839	66503	85.1575	78384

Table 4: Moment of Inertia of Spars; Torque Box Design, Cumulative Torque and Shear Flow on Wing

Sections on the wing (mm)	Moment of inertia of front spar (mm^4)	Moment of inertia of rear spar (mm^4)	CG of torque box from rear spar position (mm)	Cumulative Torque (N-mm)	Shear Flow (N/mm)
TIP-1127	-	-	0	-	-
S1-1014.3	23.3	21.6	47.122	67.1	0.0163
S2-901.6	94.2	87.4	50.007	214.1	0.0490
S3-788.9	215.6	200.1	52.8921	454.4	0.0984
S4-676.2	390.5	362.4	55.7771	802.4	0.1647
S5-563.5	621.6	576.9	58.6621	1273	0.2485
S6-450.8	912	846.4	61.5471	1882.1	0.3501
S7-338.1	1264.6	1173.7	64.4322	2646.4	0.4703
S8-225.4	1682.3	1561.3	67.3172	3583.1	0.6095
S9-112.7	2167.9	2012	70.2022	4710.6	0.7683
ROOT-0	2724.5	2528.5	73.0872	6047.7	0.9474

Fig 7: Moment of Inertia Calculation

```
%% Moment of Inertia calculations %%

for i=1:10
    I_fs(i)=BM_fs(i)*(FS_h(i)/2)/Ultimate_Tensile_strength
end
```

Fig 8: Torque Box Area Calculation

```
% Area of the torque box %

for j=2:11
    Area_TB(j)=0.5*(FS_h(j-1)+RS_h(j-1))*c_dash(j)
end
```

Table 5: Moment of Inertia of Web

Sections on the wing (mm)	Moment of inertia of web for front spar (mm^4)	Moment of inertia of web for rear spar (mm^4)
TIP- 11227	0	0
S1-1014.3	1.5715	1.1203
S2-901.6	3.3437	2.3069
S3-788.9	5.3181	3.7226
S4-676.2	7.4971	5.2064
S5-563.5	9.8834	6.8137
S6-450.8	12.4804	8.5461
S7-338.1	15.2916	10.4055
S8-225.4	18.3209	12.3936
S9-112.7	21.5724	14.5125
ROOT-0	25.0502	16.7643

Fig 9: Shear Force Due to Torsion; Total Shear in Front Spar

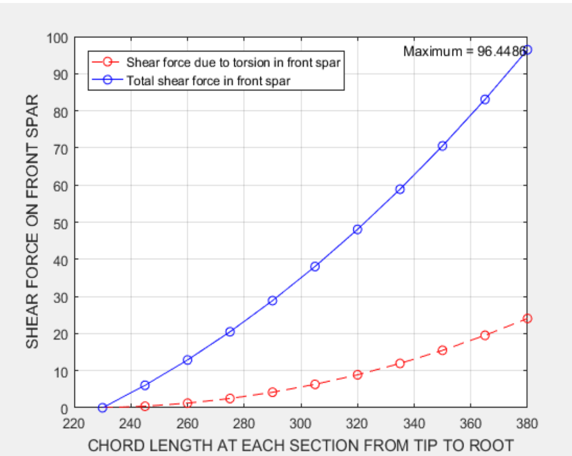


Fig 10: Shear Force Due to Torsion; Total Shear in Rear Spar

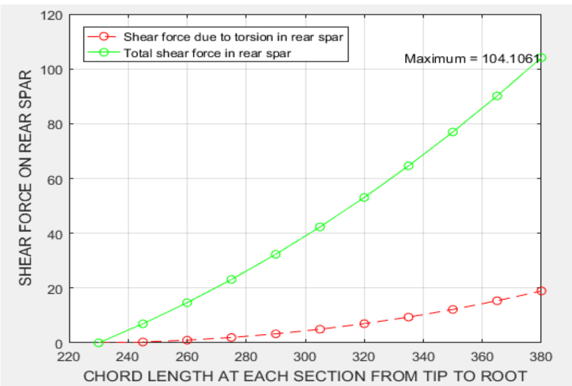


Fig 11: Internal Structure of the Wing (Isometric View)

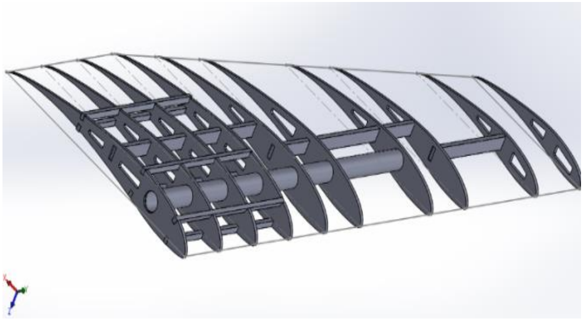


Fig 12: Internal Structure of the Wing (Top View)

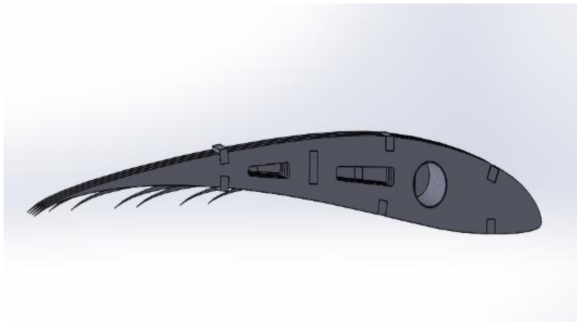


Table 6: Mechanical Parameter Values for Spar

STRUCTURAL PARAMETERS	VALUE
Max Principal stress	83.2 Mpa
Max Von-Mises stress	56.2 MPa
Max Strain Energy	8.04e9 J
Max equivalent elastic strain	.00079
Total deformation	7 mm
Yield strength of AA 6061 T-6	310 MPa
Safety factor	3.73

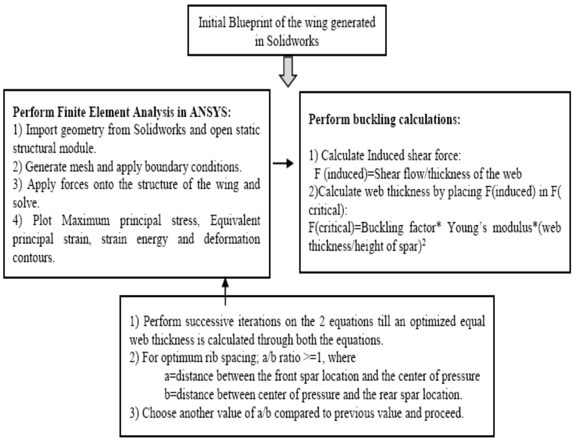
4.0 Detailed Design Phase

The detailed design phase starts with the analysis of the initial blueprint of the wing using some initial hand calculations and Finite Element solver like ANSYS. The results are then optimized for appropriate weight reduction.

The structural optimization flowchart is as follows. The whole process is an iterative one, ie. Iterations keep taking place till we get the optimized result.

4.1 Detailed design flowchart

Fig 13: Structural Optimization Flowchart



The flowchart shown as figure 13, terminates at the point in MATLAB when, for a particular value of a/b and web thickness, the mass reduces and subsequently gets verified through Finite Element solver ie. ANSYS through stress and strain contour plots with a significant reduction in a value.

4.2 Finite element analysis

Finite Element Analysis is a computerized method which is used to predict the behavior of a mechanical model in response to an applied force, provided a set of boundary conditions. The modelled wing on Solidworks is now analyzed in ANSYS, a finite element solver when the wing is exposed to various mechanical forces of varying magnitudes. The material properties for the ribs was added in ANSYS for balsawood and birchwood

Fig 14: Failed & Obsolete Mesh (1st Attempt)

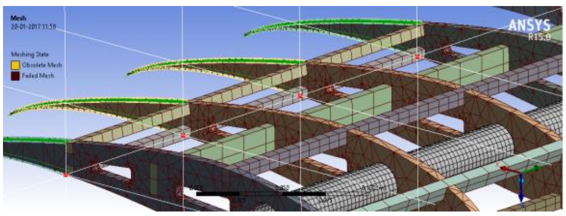


Fig 15: Mesh Statistics

Statistics	
Nodes	63144
Elements	17849
Mesh Metric	None

Fig 16: Successfully Generated Mesh

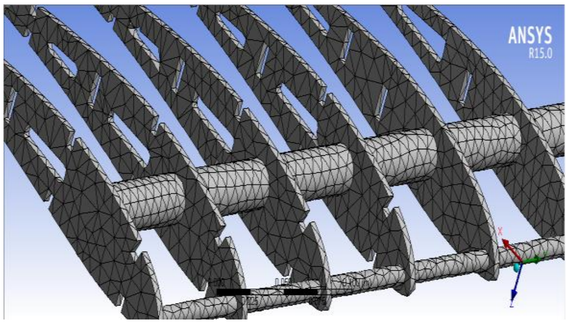


Fig 17: Tetrahedron Element Close-Up

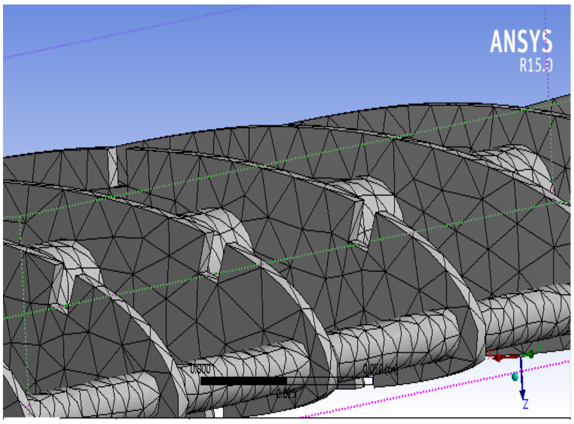


Fig 18: Force Application on the Wing

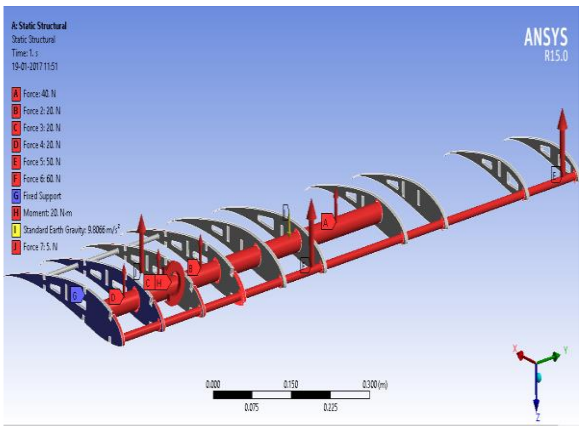


Fig 19: Equivalent Von-Mises Stress Contours

Fig 20: Strain Energy Contours

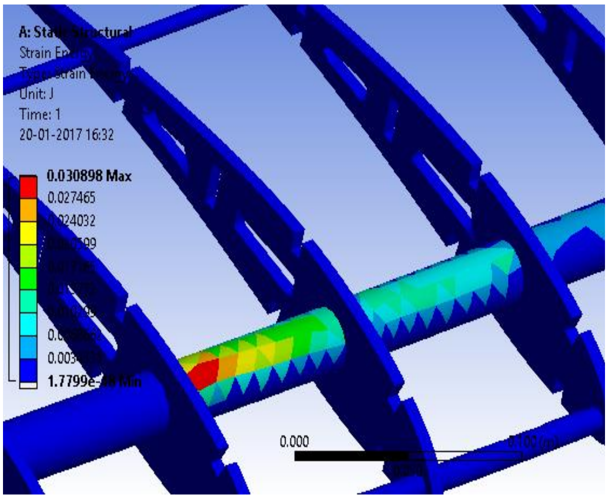
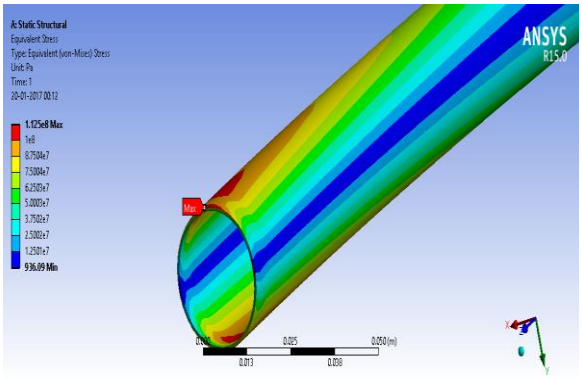


Fig 21: Equivalent Von-Mises Stress Contours in Spar



When the CAD model of the wing was first imported in ANSYS and the mesh was generated, the mesh failed at certain contact points of the assembly, shown by red blips in Fig.12. It was observed that the meshing method was not accurate and the element size was large at thin trailing edges which led to failure at such points. The meshing method was then changed to Tetrahedron elements with a Patch Independent algorithm limited by maximum element size. The mesh was then generated successfully.

The meshed wing is now opened in ANYS Mechanical and 4 types of force are applied onto the entire structure

1) Uniformly varying load on the front supporting spar
2) Uniformly varying load on the primary AA 6061 T-6 spar
3) Moment along the transverse axis of the wing
   Standard earth gravity on all bodies

Table 7: Mechanical Parameter Values for the Internal Structure

STRUCTURAL PARAMETERS	VALUE
Max principal stress	68 MPa
Max Von-Mises stress	70 MPa
Max strain energy	30 mJ
Max equivalent elastic strain	0.139 mJ
Normal stress	17.87 MPa
Total deformation	11.8 cm

Table 8: Weight Optimization by Changing the Position of Front Spar, Keeping Rear Spar Fixed

Iteration	Position of front spar from leading edge	Position of rear spar from leading edge	a/b ratio	Total mass of the spars (gm)
1	25 %	62%	1.17647	316.71
2	22%	62%	1.353	310.55
3	20%	62%	1.4706	302.88
4	18%	62%	1.588	299.25
5	30 %	62 %	0.8823	323.10 s

By shifting the position of the front spar ie. Increasing a/b ratio, a maximum reduction of 17.46 gms was achieved, but the placement of spar was not feasible at 18% chord. Hence, the placement of spar at 22% chord was finally selected with the total mass of spars equaling 310.55 gms.

5.0 Conclusions

The paper demonstrates the design methodology undertaken in the structural design and optimization of a UAV wing for the SAE India Aero Design Challenge 2017. The final analysis and calculations can be accepted of a structurally fit pair of wings for the UAV.

The most influential parameter of the competition ie. Payload capacity seems to be fulfilled through this design, as the wing is designed for a lift load factor of 5. The final simulation on the wing also gave us a safety factor of 3.73 which validates it completely.

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