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Research Article

Computational Analysis for Random Winglet Designs on Light Aircraft

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Abstract

This paper describes 3-dimensional wing-winglet analysis that was performed on random winglet designs on varying cross-sections of air foil. A total of four random wing-winglet pairs have been studied and their performance has been investigated according to their suitability on a light aircraft. The performance characteristics have been studied with CFD solver, static structural analysis for aluminum alloy material, when subjected to loads and moments experienced during turbulence and transient thermal analysis with initial temperature being 278 K and increasing up to 373 K. The heat flux at the first contact point of fluid-body interface is taken to be about 373 K; various simulation solutions have been developed. The angle of attack of the wing has been varied 0–15 degree with increments of 5, and lift to drag (L/D) ratio, drag coefficient have been found.

Keywords: CFD-light aircraft, Light aircraft aerodynamics, Winglet analysis, Random winglets, Light aircraft wing performance characteristics

Introduction

Winglets on an aircraft wing help reduce the included drag and thus the vortices produced during various instances of flight. They also increase the aspect ratio of the wing without having to increase the actual span of the wing materially. Studies at Boeing have shown apart from the above, increase in block-fuel efficiency, reduction of take-off length, and also increase in the effectiveness of braking upon touchdown.[13]

The motivation of this research has been to explore random designs of winglets on varying cross-sectional areas, effectiveness of wingtip considerations, measured effects of such surfaces on extreme aerodynamic forces, moments, and loads near and beyond their design considerations.

The un-natural conditions tested include wind tunnel speeds of 0.28 Mach, angle of attack where lift is very low and the initial assumption that the obtained data would be helpful for understanding initialization conditions before stall of small aircraft.

Wind Tunnel Terminology

M=mass flow rate

A=area

p=density

m=mach

y=specific heat ratio

p=pressure

v=velocity

a=speed of sound

Conversion of mass: m=pVA=constant dp\p+dV/V+dA/a=0

Conversion of momentum: pVdV=−dp

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Isentropic flow: dp/p=ydp/p dp=a2 dp

Combine with momentum:−M2dV/V=dp/p

combine with mass: (1−M2)dV/V=−dA/A

Increase in area (dA>0):

dV<0 (velocity decreases) dp>0(pressure increases)

for supersonic flow(m>1)

dV>0 (velocity increases) dp<0 (pressure decreases)

Boundary Conditions

The pressure and temperature values for cruising level are taken as below:

Table 1.Atmospheric Properties at 0 km Altitude Considered

S. No.	Variables	Properties
1.	Temperature	288.0 K
2.	Pressure	1 atmosphere
3.	Density	1.225 kg/m^3
4.	Viscosity	1.7894E-5 kg/ms

The project has been done in 3 stages, namely:

Random winglet designs – total of 4 designs have been extracted from CAD Platforms online.

The wing-winglet have been subjected to:

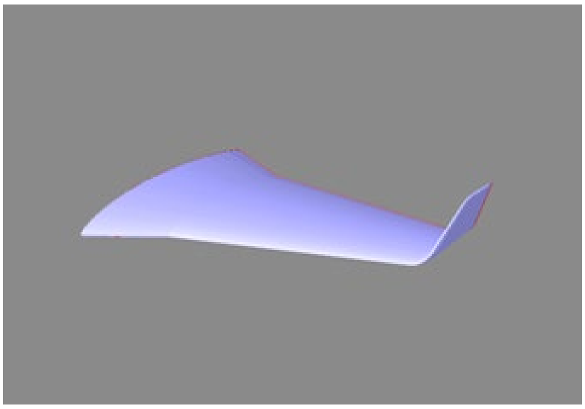
- CFD analysis at Mach 0.28
- Virtual wind tunnel testing
- Structural analysis with aluminum alloy as base material

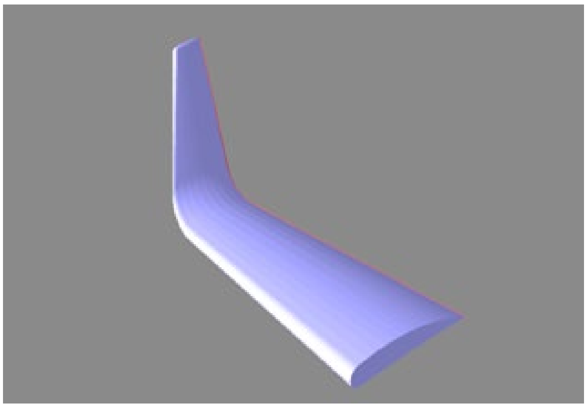
1. Transient thermal analysis for heat flux distribution and temperature variation

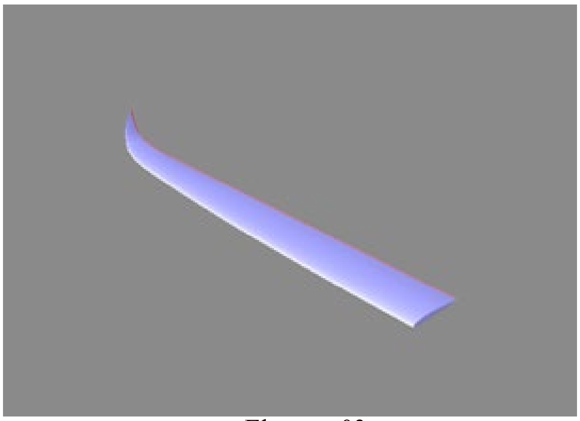
- CFD Analysis at Mach 0.85
- Virtual wind tunnel testing

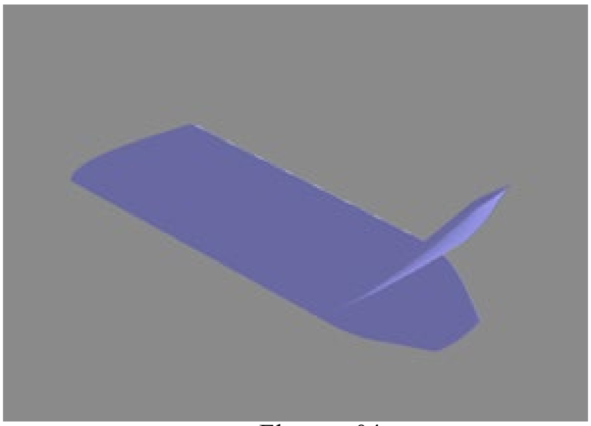
2. Various graphs for aerodynamic characteristics of wings with winglets and simulation results have been included.

Stage 1: Four Random Designs of Wing-winglet have been chosen as follows:


Element 01


Element 02


Element 03


Element 04

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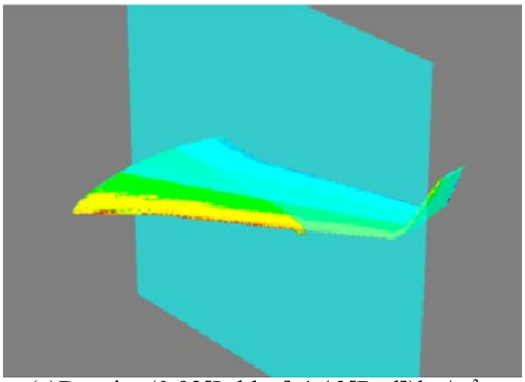
Stage 2: The above winglets were analyzed subject to:

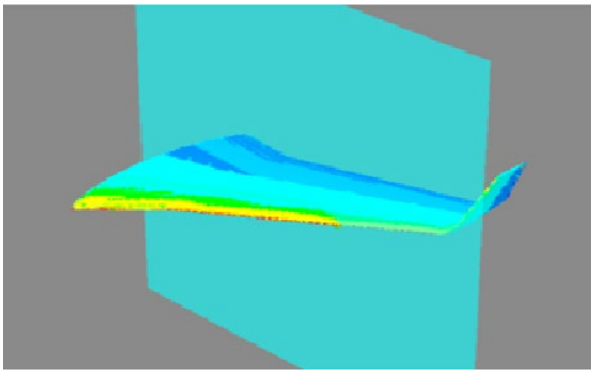
- CFD analysis at 0.28 Mach

Element 01

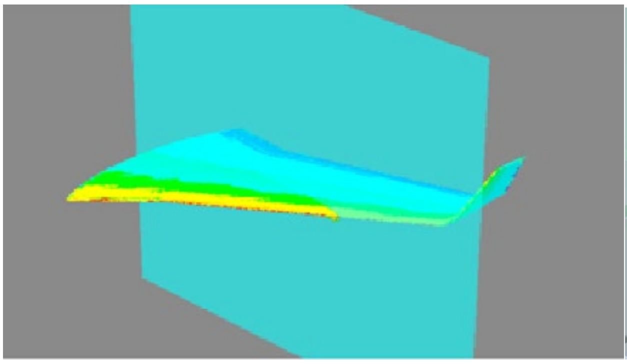
The element 01 was subjected to CFD analysis and simulations results of parameters, such as density, temperature and pressure, are as follows. The results show the maximum variation and load due to the physical parameters on the wing acting on the point of first contact between air and the wing body.

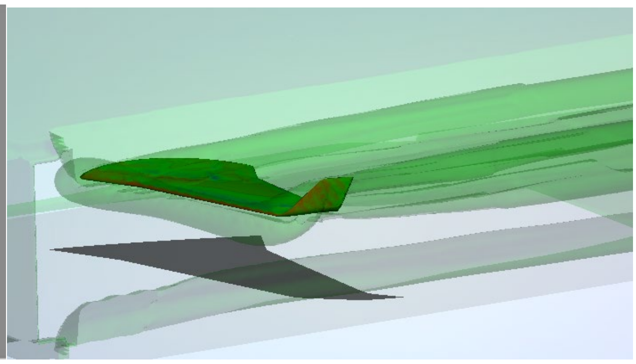
In the below results, the material is of irrelevance, the load distribution and aerodynamics of the wing-winglet have been visually analyzed and some of the data obtained was used for further analysis.





(a)Density (0.92[L-blue]-1.13[Red])kg/m^3 (b)Pressure (0.92[blue]-1.98[Red]) Pa





(c) Temperature=288 K (d) Airflow model

Initialization

Material: Aluminum alloy (AL)

Structural

The analysis using ANSYS 18.2 has been conducted on the wing-winglet design element 01; one of the wings was fixed, i.e., where the body is attached to the wing. A force of 1000 N was applied on the throughout top section of the wing, moments of 1000 N-m, 2000N-m were applied at the appropriate position on the wingtip and also on the winglet.

Thermal

Minimum temperature=288 K and Maximum temperature=373 K, temperature is varied, the point of contact between fluid and the wing is specified as boundary conditions. The input parameters for structural and thermal are as below:

Definition					
Type	Fixed Support	Force	Moment		Fluid Solid Interface
Suppressed	No				
Define By		Components			
Coordinate System		Global Coordinate System			
X Component		0. N (ramped)	0. N·m (ramped)	-1000. N·m (ramped)	
Y Component		0. N (ramped)	1000. N·m (ramped)	0. N·m (ramped)	
Z Component		-2000. N (ramped)	0. N·m (ramped)		
Behavior			Deformable		
Interface Number					1.
Data to Transfer [Expert]					Program Controlled

TABLE 11
Model (C2) > Transient Thermal (C3) > Solution (C4) > Solution Information

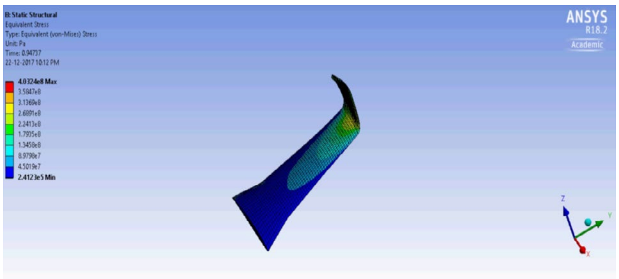
Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 12
Model (C2) > Transient Thermal (C3) > Solution (C4) > Solution Information > Result Charts

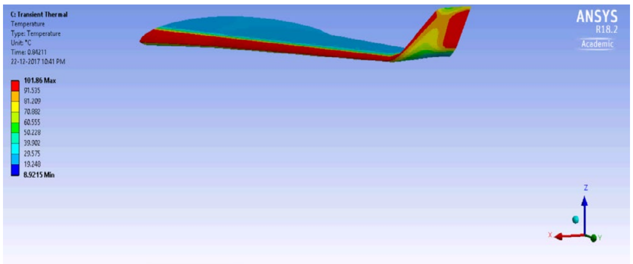
Object Name	*Temperature - Global Maximum*	*Temperature - Global Minimum*
State	Solved	
Definition		
Type	Temperature	
Suppressed	No	
Scope		
Scoping Method	Global Maximum	Global Minimum
Results		
Minimum	100. °C	8.9215 °C
Maximum	101.87 °C	24.766 °C

Results

The equivalent stress due to the load and its distribution, temperature distribution, total heat flux and directional heat flux for element 01 is shown below.

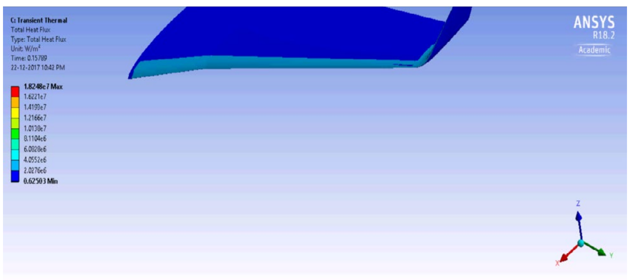


(a) Static structural analysis of element 01

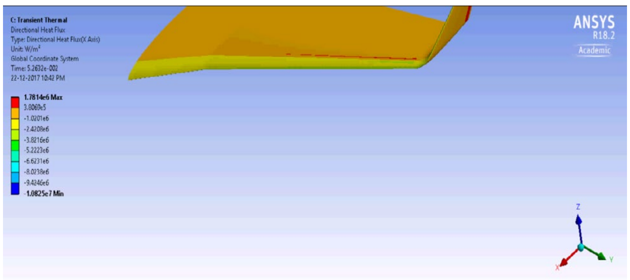


(b) Transient thermal analysis of element 01

For equivalent stress in Pa for temperature variation in Celsius



(c) Transient Thermal Analysis of Element 01



(d) Transient Thermal Analysis of Element 01

For total heat flux in w/m^2 for directional heat flux in w/m^2

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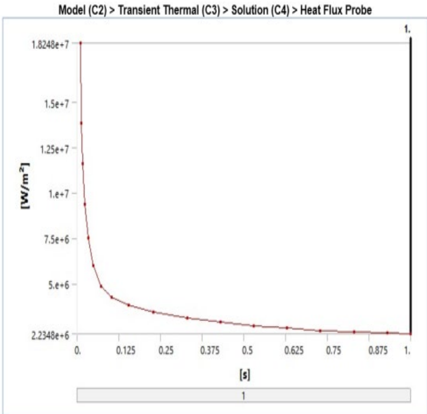
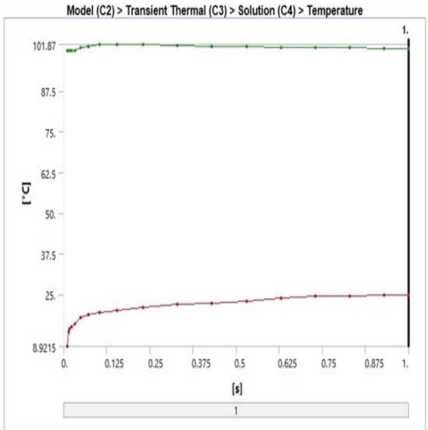


(e)Transient Thermal Analysis for Element 01



(f) Transient Thermal Analysis for Element 01

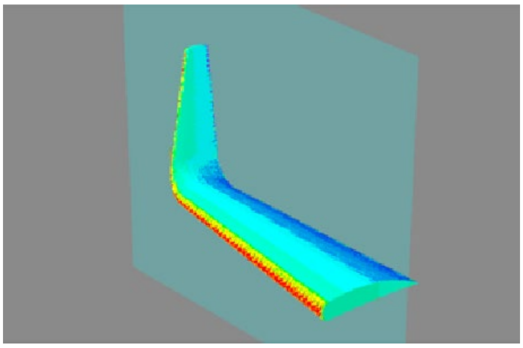
For solution v/s heat flux probe for solution v/s temperature

Results					
Minimum	0. m	-4.8374e-004 m	2.4146e+005 Pa	3.4185e-006 m/m	4.9075e-006 J
Maximum	1.4214e-002 m	6.9291e-003 m	6.9032e+008 Pa	1.5023e-002 m/m	0.20653 J
Minimum Occurs On	PRT0002				
Maximum Occurs On	PRT0002				
Information					
Time	1. s				
Load Step	1				
Substep	1				
Iteration Number	1				
Integration Point Results					
Display Option			Averaged		
Average Across Bodies			No		

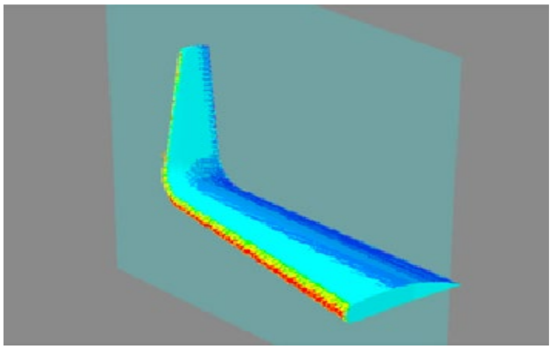
Element 02

Element 02 was subjected to CFD analysis and simulation results of parameters such as density, temperature and pressure is as follows, the results show the maximum variation and load due to the physical parameters on the wing acting on the point of first contact between air and the wing body.

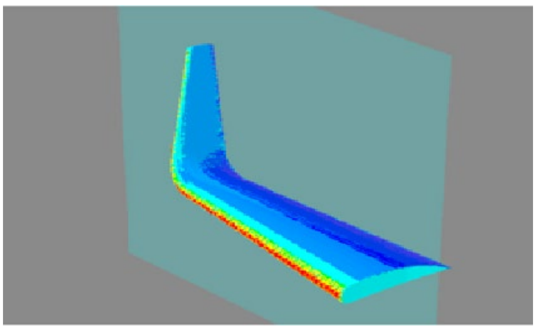
In the below results, the material is of irrelevance, the load distribution and aerodynamics of the wing-winglet have been visually analyzed and some of the data obtained was used for further analysis.



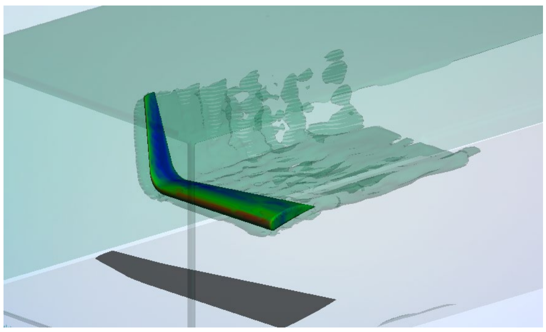
(a)Density (0.92[L-blue]-1.13[Red]) kg/m^3



(d) Airflow Model



(c)Temperature=288 K



(b) Pressure (0.92[L-blue]-1.98[Red]) Pa

Initialization

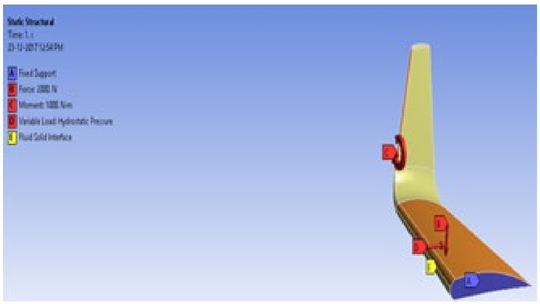
Material: Aluminum alloy (AL)

Structural

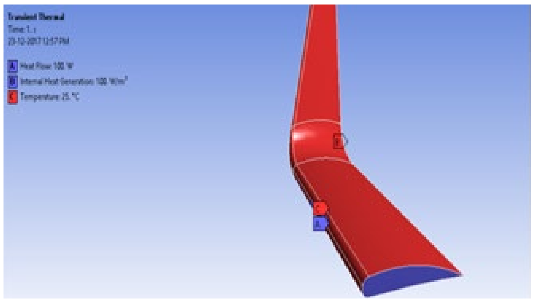
The analysis using ANSYS 18.2 has been conducted on the wing-winglet design element 01. One of the wings was fixed, i.e., where the body is attached to the wing. A force of 1000N was applied on throughout the top section on the wing, moments of 1000 N-m, 2000N-m were applied at the appropriate position on the wingtip and also on the winglet.

Thermal

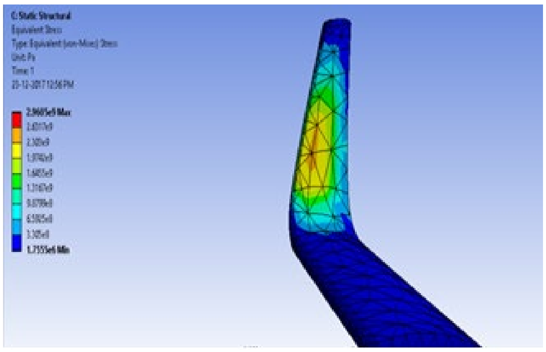
Minimum temperature=288 K and maximum temperature=373 K; temperature is varied, the point of contact between fluid and the wing is specified as boundary conditions. The input parameters for structural and thermal are as below:



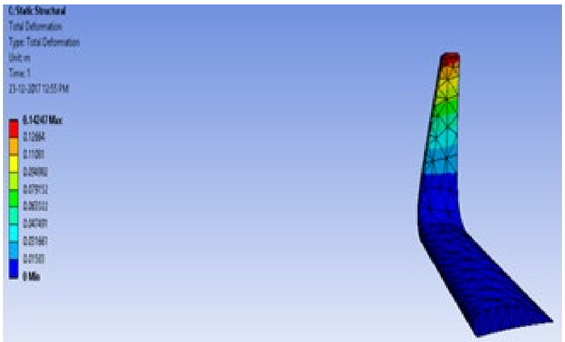
(a) Static Structural Analysis for Element 02



(b) Transient Thermal Analysis for Element 02

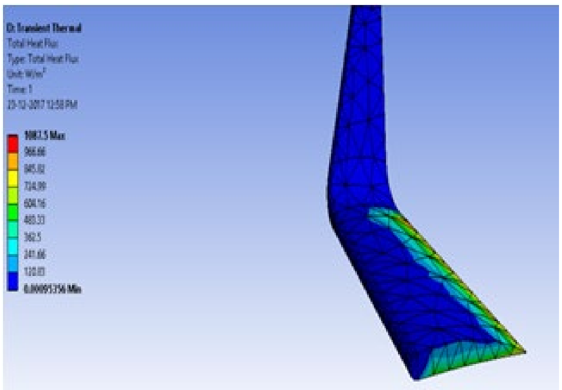


(c) Static Structural Analysis of Element 02

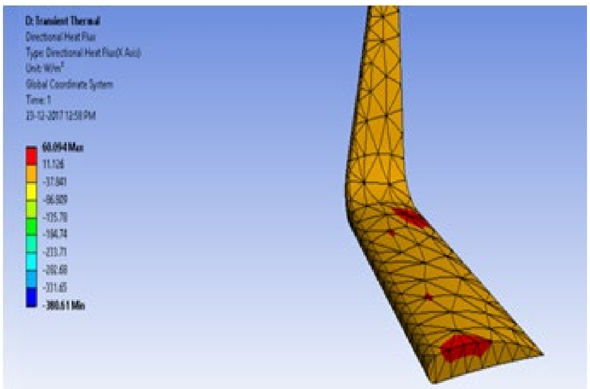


(d) Static Structural Analysis of Element 02

For equivalent stress in Pa for total deformation in m



(f) Transiel Thermal Analysis of Element 02



(e) Transient Thermal Analysis of Element 02

For total heat flux in w/m^2 for directional heat flux in w/m^2

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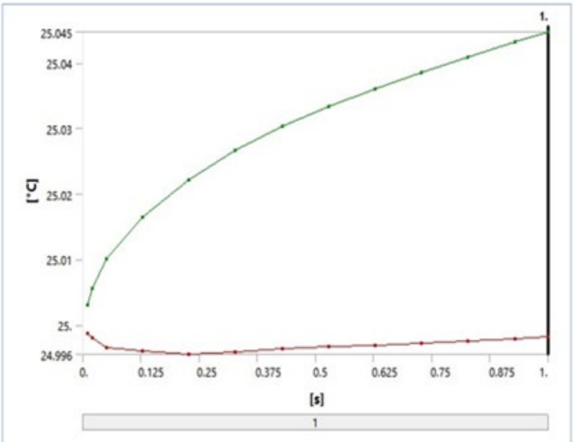
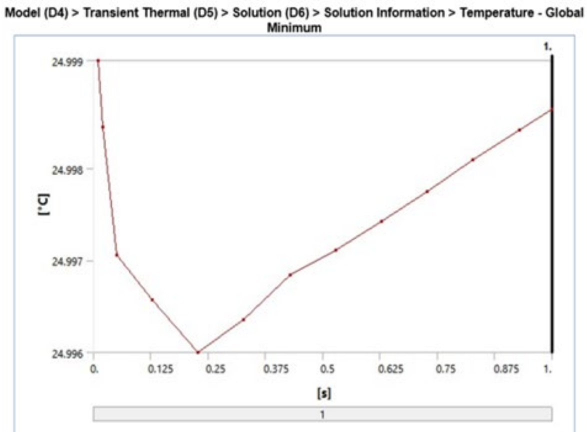
Results

The equivalent stress due to the load and its distribution, temperature distribution, total heat flux and directional heat flux for element 02 is shown below.

Object Name	*Temperature*	*Total Heat Flux*	*Directional Heat Flux*	*Thermal Error*
State	Solved			
Scope				
Scoping Method	Geometry Selection			
Geometry	All Bodies			
Definition				
Type	Temperature	Total Heat Flux	Directional Heat Flux	Thermal Error
By	Time			
Display Time	Last			
Calculate Time History	Yes			
Identifier				
Suppressed	No			
Orientation			X Axis	
Coordinate System			Global Coordinate System	



(g) Transient thermal analysis of element 02



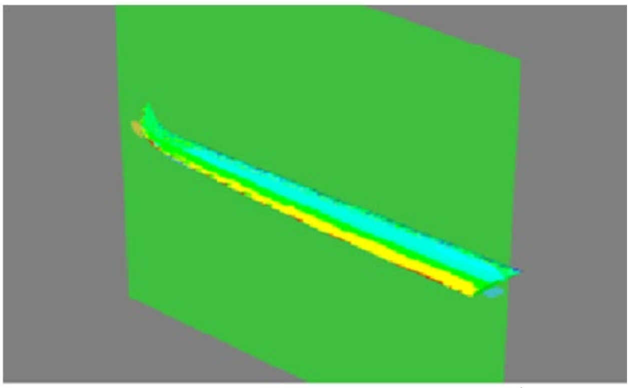
(h) Transient thermal analysis of element 02

For solution v/s temperature for solution v/s solution information overTemperature.

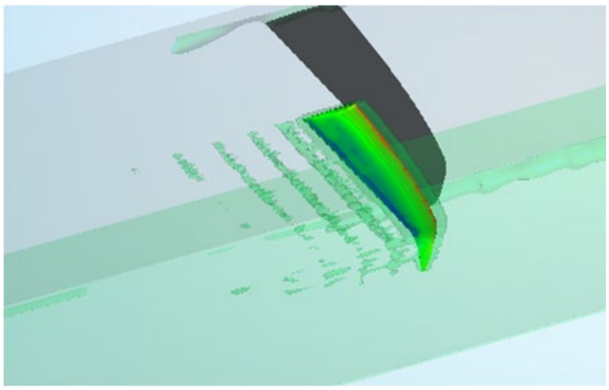
Element 03

The element 03 was subjected to CFD analysis and simulation results of parameters such as density, temperature and pressure are as follows. The results show the maximum variation and load due to the physical parameters on the wing acting on the point of first contact between air and the wing body.

In the below results, the material is of irrelevance, the load distribution and aerodynamics of the wing-winglet have been visually analyzed and some of the data obtained was used for further analysis.



(a) Density (0.92[L-blue]-1.13[Red]) kg/m^3



(b) Airflow

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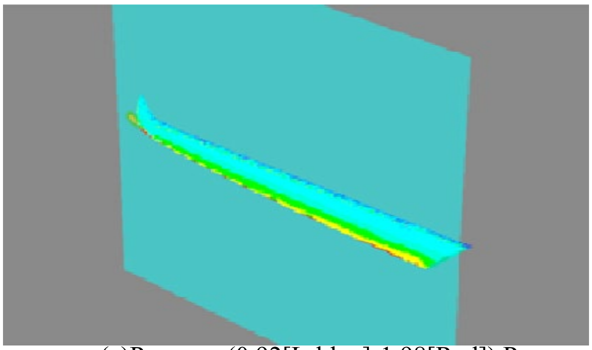
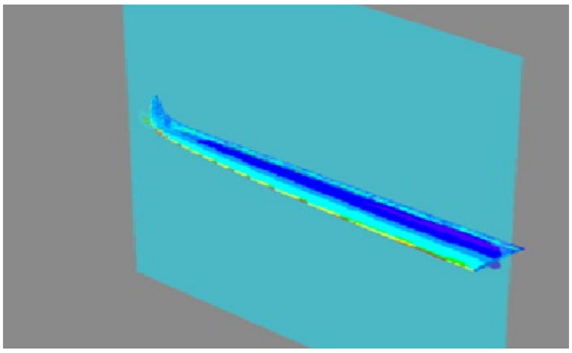


(c)Pressure (0.92[L-blue]-1.98[Red]) Pa



(d) Temperature=288 K

Initialization

Material: Aluminum alloy (AL)

Structural

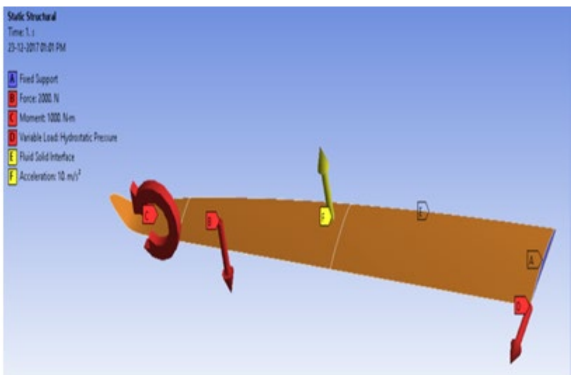
The analysis using ANSYS 18.2 has been conducted on the wing-winglet design element 01. One of the wings was fixed, i.e., where the body is attached to the wing. A force of 1000N was applied on throughout the top section on the wing, moments of 1000 N-m, 2000N-m were applied at the appropriate position on the wingtip and also on the winglet.

Thermal

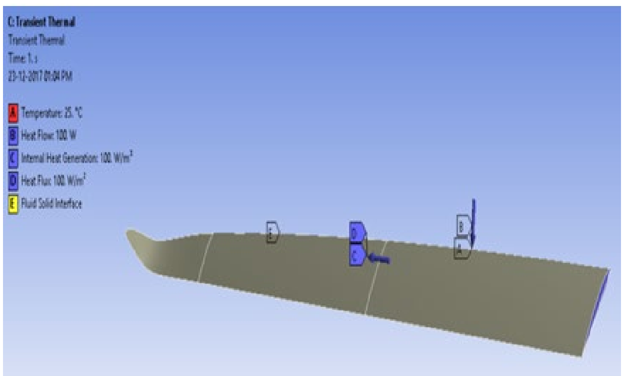
Minimum temperature=288 K and Maximum temperature=373 K; temperature is varied, the point of contact between fluid and the wing is specified as boundary conditions. The input parameters for structural and thermal are as below:

Model (B4, C4) > Static Structural (B5) > Loads

Object Name	*Fixed Support*	*Force*	*Moment*	*Hydrostatic Pressure*	*Fluid Solid Interface*
State	Fully Defined				
Scope					
Scoping Method	Geometry Selection				
Geometry	1 Face			3 Faces	6 Faces
Definition					
Type	Fixed Support	Force	Moment	Hydrostatic Pressure	Fluid Solid Interface
Suppressed	No				
Define By		Components			
Coordinate System		Global Coordinate System			
X Component		0. N (ramped)	0. N·m (ramped)		
Y Component		0. N (ramped)	-1000. N·m (ramped)		
Z Component		-2000. N (ramped)	0. N·m (ramped)		
Behavior			Deformable		
Fluid Density				1.225 kg/m³	
Interface Number					1.
Data to Transfer [Expert]					Program Controlled



(a) Static Structural Analysis for Element 03



(b) Transient Thermal Analysis for Element 03

Results

The equivalent stress due to the load and its distribution, temperature distribution, total heat flux and directional heat flux for element 01 is shown below.

Under the action of moments and forces, the wing structurally failed.

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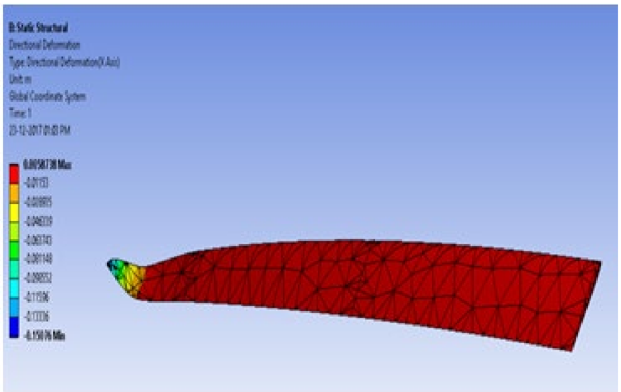
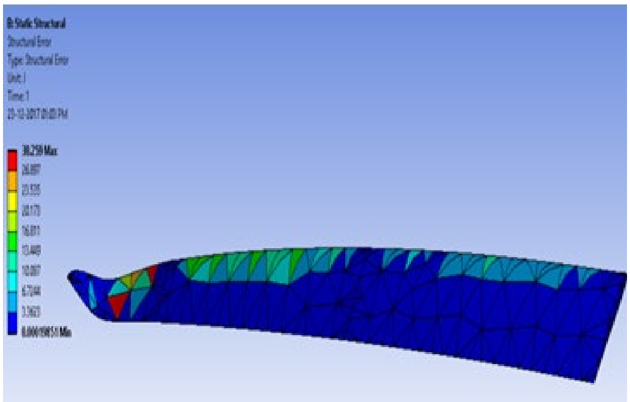
Results								
Minimum	-0.15076 m	0. m	5.0606e-004 m/m	3.885e+006 Pa	4.2144e-004 J	-4.2062e+008 Pa	1.9851e-004 J	5.0606e-004 m/m
Maximum	5.8738e-003 m	0.85209 m	2.5323e-002 m/m	1.0062e+009 Pa	12.662 J	1.0781e+009 Pa	30.259 J	2.5323e-002 m/m
Minimum Occurs On	MODEL3							
Maximum Occurs On	MODEL3							
Information								
Time	1. s							
Load Step	1							
Substep	1							
Iteration Number	1							
Integration Point Results								
Display Option			Averaged			Averaged		Averaged
Average Across Bodies			No			No		No

Model (B4, C4) > Transient Thermal (C5) > Solution (C6) > Results

Object Name	*Temperature*	*Total Heat Flux*	*Directional Heat Flux*	*Thermal Error*
State	Solved			
Scope				
Scoping Method	Geometry Selection			
Geometry	All Bodies			
Definition				
Type	Temperature	Total Heat Flux	Directional Heat Flux	Thermal Error
By	Time			
Display Time	Last			
Calculate Time History	Yes			
Identifier				
Suppressed	No			
Orientation			X Axis	
Coordinate System			Global Coordinate System	
Results				
Minimum	25. °C	1.0269e-005 W/m²	-98.698 W/m²	2.8604e-017
Maximum	25.004 °C	175.72 W/m²	8.1669 W/m²	9.0984e-005
Minimum Occurs On	MODEL3			
Maximum Occurs On	MODEL3			
Minimum Value Over Time				
Minimum	24.999 °C	5.2795e-006 W/m²	-98.698 W/m²	1.2912e-018
Maximum	25. °C	1.1082e-005 W/m²	-24.644 W/m²	2.3406e-015
Maximum Value Over Time				
Minimum	25. °C	41.641 W/m²	7.8615 W/m²	1.9638e-006
Maximum	25.004 °C	175.72 W/m²	17.639 W/m²	9.0984e-005
Information				
Time	1. s			
Load Step	1			

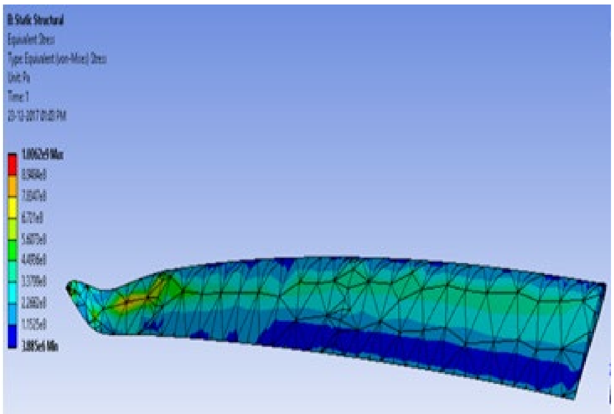


(c) Static Structural Analysis of Element 03

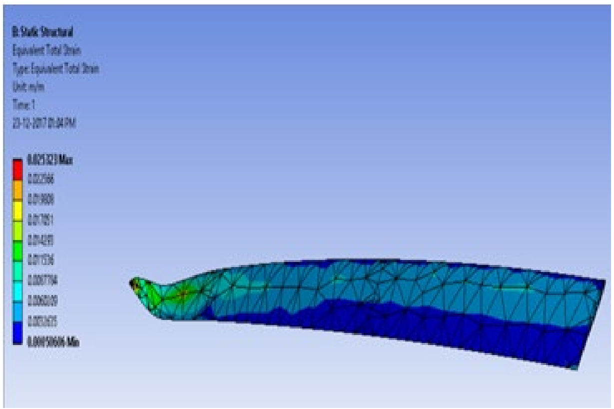


(d) Static Structural Analysis of Element 03

For directional deformation in m for structural error.

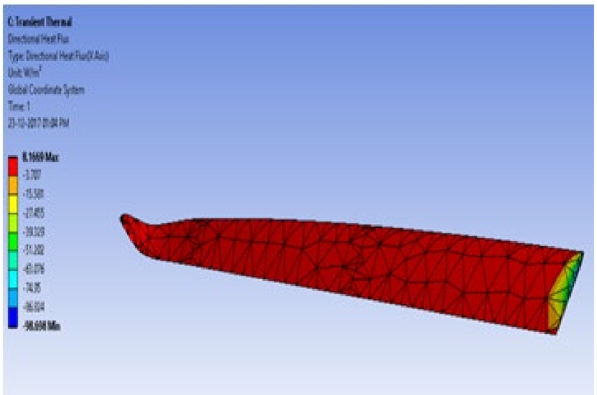


(e) Static Structural Analysis of Element 03

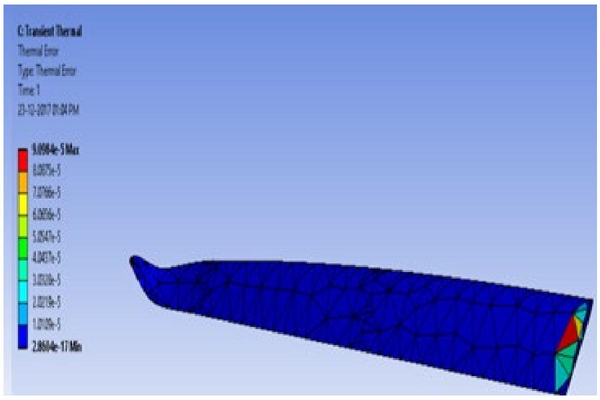


(f) Static Structural Analysis of Element 03

For equivalent stress in Pa for equivalent total strain.

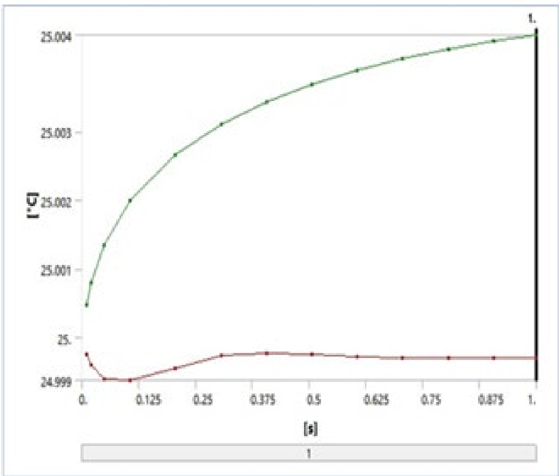


(g) Transient Thermal Analysis of Element 03

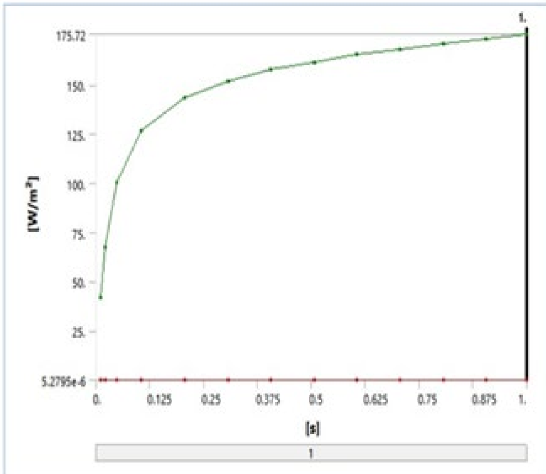


(h) Transient Thermal Analysis of Element 03

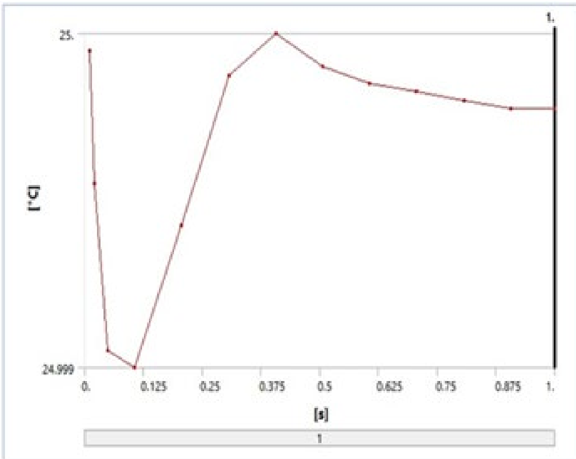
For directional heat flux in w/m^2 for thermal error.



(a) Transient Thermal Analysis of



(b) Transient Thermal Analysis of



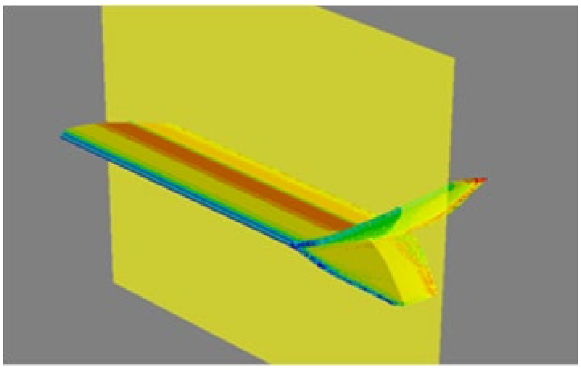
(C) Transient Thermal Analysis of Element 03 for Sol./s Temp.
Element 03 for Sol. v/s Total Element 03 for Sol. v/s Sol. Info

Heat flux over temperature

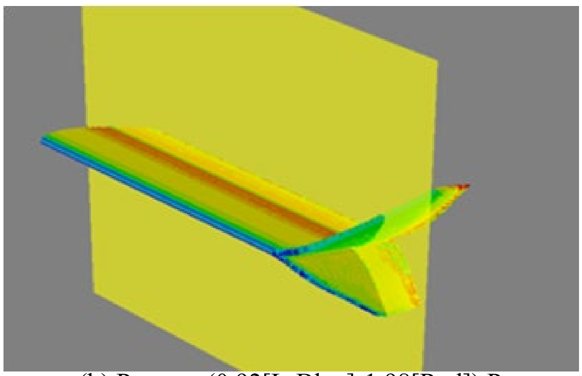
Element 04

Element 04 was subjected to CFD analysis and simulation results of parameters such as density, temperature and pressure are as follows; the results show the maximum variation and load due to the physical parameters on the wing acting on the point of first contact between air and the wing body.

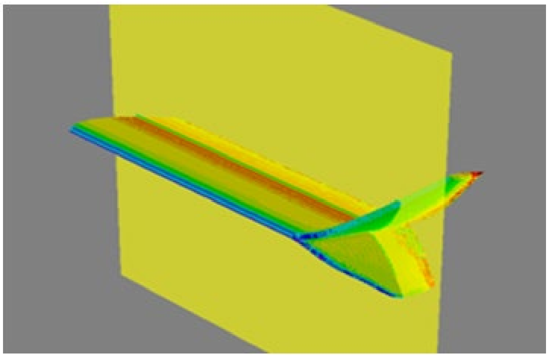
In the below results, the material is of irrelevance, the load distribution and aerodynamics of the wing-winglet have been visually analyzed and some of the data obtained was used for further analysis.



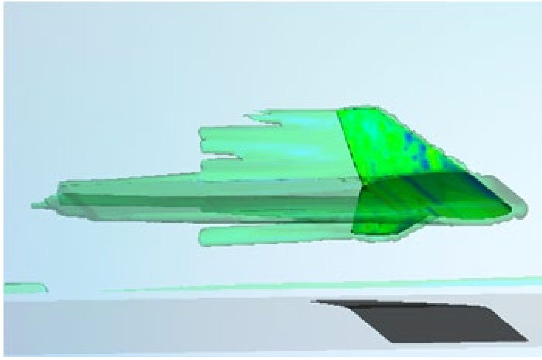
(a) Density (0.92[L-Blue]-1.13[Red])kg/m^3



(b) Pressure(0.92[L-Blue]-1.98[Red]) Pa



(c)Temperature 288 K



(d) Airflow

CFD Analysis at 0.85 Mach

All four elements were subjected to CFD analysis and simulation results of parameters such as density, temperature and pressure are as follows; the results show the maximum variation and load due to the physical parameters on the wing acting on the point of first contact between air and the wing body.

In the below results, the material is of irrelevance, the load distribution and aerodynamics of the wing-winglet have been visually analyzed and some of the data obtained was used for further analysis.

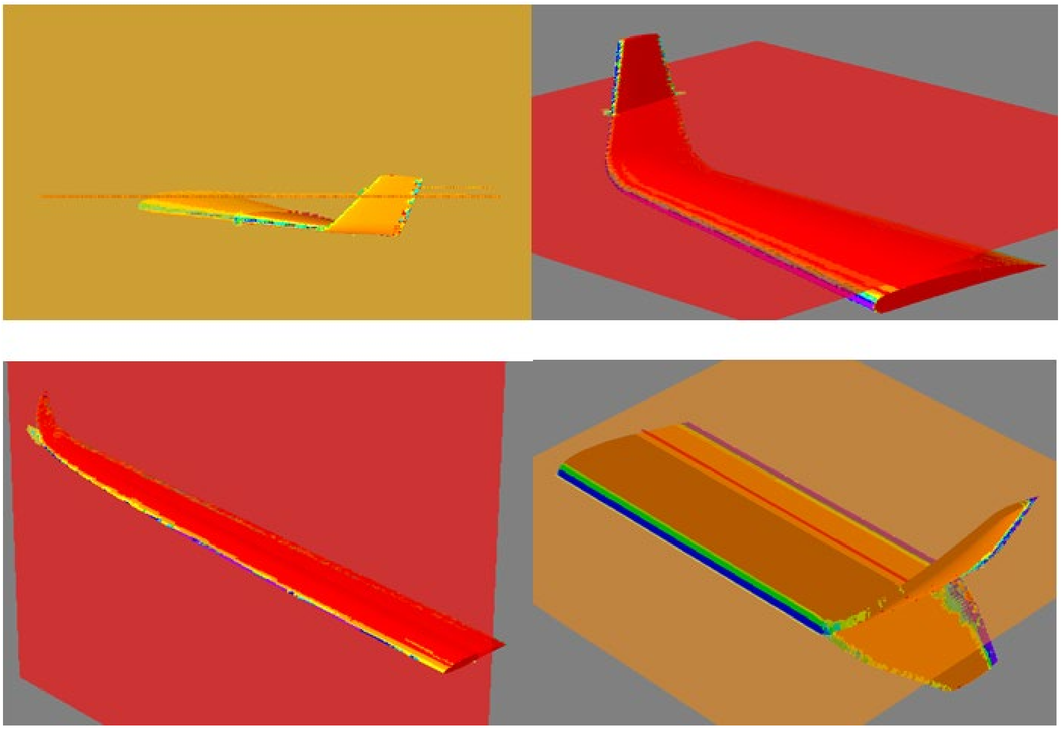


Figure Airflow Analysis at 0.85 Mach

Results

From the three-stage simulation results of the above, we derived the aerodynamic, structural and thermal conclusions.

Drag coefficient value for 50 m/s and 100 m/s have been calculated for all the wings. They are as follows:

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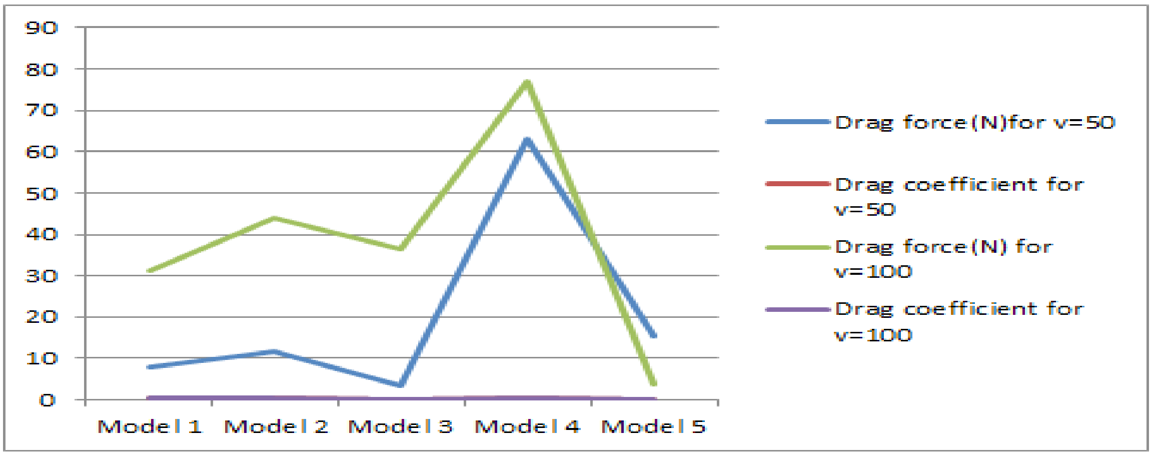
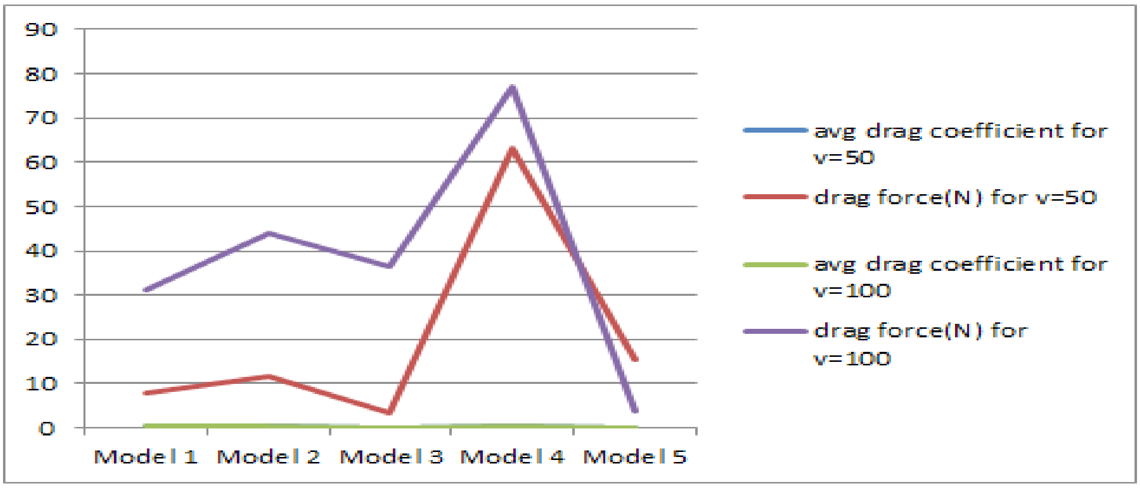
Winglet Model	Drag Force(N) for v=50m/s	Drag Coefficient for v=50m/s	Drag Force(N) for v=100 m/s	Drag Coefficient for v=100 m/s
Model 1	7.802	0.23	31.247	0.23
Model 2	11.493	0.56	43.888	0.53
Model 3	3.433	0.08	36.422	0.21
Model 4	63.049	0.4	77.15	0.38



Average drag coefficient, drag value for 50 m/s and 100 m/s have been calculated for all the wings.

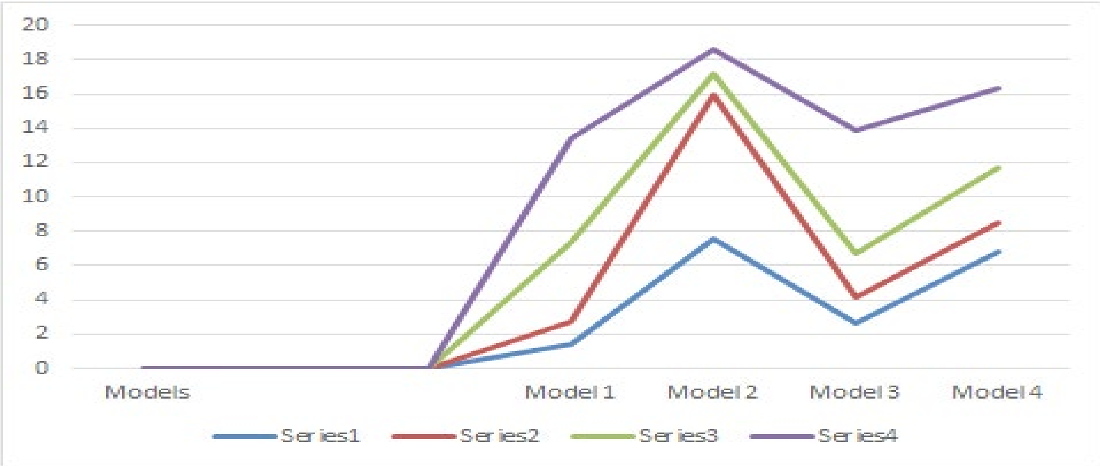
They are follows:

winglet Model	Avg drag Coefficient for v=50 m/s	Drag Force(N) for v=50 m/s	Avg Drag Coefficient for v=100 m/s	Drag Force (N) for v=100 m/s
Model 1	0.27	7.802	0.26	31.247
Model 2	0.37	11.493	0.48	43.888
Model 3	0.08	3.433	0.14	36.422
Model 4	0.37	63.049	0.31	77.15



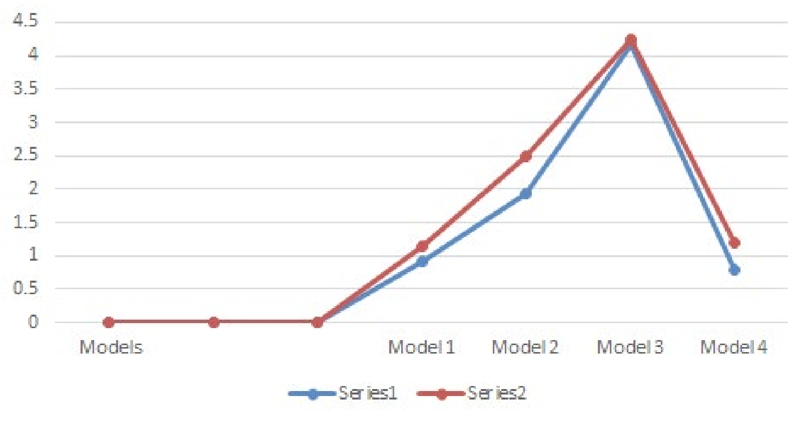
The lift for various angles of attack is given below:

Models		Lift		
	0°	5°	10°	15°
Model 1	1.43	1.358	4.569	6.094
Model 2	7.529	8.44	1.191	1.452
Model 3	2.691	1.463	2.568	7.119
Model 4	6.758	1.736	3.202	4.594



Lift coefficient v/s Drag coefficient is given below:

Models	Lift Coefficient*10^{-4}	Drag Coefficient
Model 1	0.927	0.23
Model 2	1.94	0.56
Model 3	4.175	0.08
Model 4	0.795	0.4



Ratio of lift coefficient and drag coefficient v/s lift coefficient is given below:

Models	**Lift Coefficient/Drag Coefficient**	**Lift Coefficient*10^{-4}**
Model 1	4.03	0.927
Model 2	3.46	1.94
Model 3	52.187	4.175
Model 4	1.99	0.795

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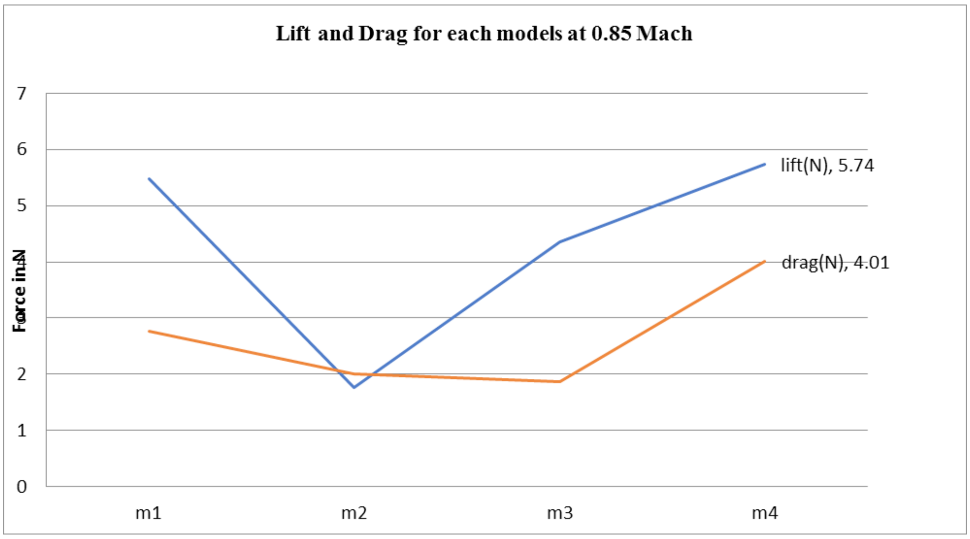
Lift and Drag at 0.85 Mach are given below:



Aerodynamic characteristics solution for all the elements:

For element 1 and element 2, lift is maximum at 15 degree and 5 degree respectively. But element 3 and element 4 fail to provide required lift accurately at low angle, while element 3 provides high lift at larger angle; because of this, the nose of the aircraft tilts upwards and loses flight and stalls.

Lift of element 1 gradually increases with increase in angle of attack, similarly for both element 2's and element 4's lift decreases with increase in angle of attack.

Structural analysis for all the elements:

Element 1 and element 2 sustain higher stress and strain and are more resilient. It produces appreciable deformation to the load applied. The structural strength of winglet is high for the same and the strength decreases element 2>element 1>element 4>element 3.

Element 3 failure point was attained much quicker relative to others; the failure was attributed to the design considerations and shape.

Thermal analysis: It is evident from our findings that the wing gets hot at the first point of contact from the air interface. The heat conduction and convection decreases with the increase in chord length.

Conclusion

The structural analysis and aerodynamic analysis indicate that the cross-sectional area of the wing must be large enough to withstand the near-stall conditions and also turbulence caused due to the weather conditions, etc. The thermal analysis is helpful for designing a cooling system in the airplane and the hottest regions have been marked out in the simulations which enable the refrigeration engineer to accurately run the evaporators in those regions to extract the maximum heat.

Further, simulations have indicated that the hotter the front wing area beyond threshold, the aerodynamics is affected due to that apart from the weakening of the structure. The research can be referred to in future for designing the refrigeration system for various cross sections of wings with winglets and also other automated system designs for unfriendly flight conditions.

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