Design Point Estimation of Regional Transport Aircraft and Structural Analysis of Wing

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Abstract: Aircraft designers thrive to produce the most accurate design to ensure all the disciplines involved in building the aircraft attain the most flexible ways of working methodologies. Implementing the conceptual design process tends to reduce cost iterations during the design phase and also in the after-design stages. Moreover, conceptual design proves to be an inherently multidisciplinary activity involving every other department to contribute in the best way possible to understand the validation of the entire design. Ideally, the ultimate goal of the conceptual design process is to strike a balance in the trade-off between maximum take-off weight and performance characteristics.

Current aircraft designs involve increased complexity and hence pose serious challenges to the aviation industry. This has led to advancements in analytical, experimental, and computational methods. Nevertheless, the conceptual design process is yet an important aspect and the very first stage to begin an aircraft design. This not only gives a preliminary analysis of the design process but also helps the detailed design in the later development stage. Though the method is simple, it includes a vast number of functions in order to improve the accuracy provided the probability of failure is low. This phase leads to an increase in the overall reliability of the design process.

This project focuses on the design point estimation of a Regional Transport Aircraft (RTA) based on a conceptual design process, which involves the determination of maximum take-off weight and constraint analysis for performance sizing, ultimately leading to design point. Design point is utilized to estimate the wing reference area and make the engine selection. Further, using the wing reference area, the airfoil is chosen and the 3-D wing model is designed and analyzed.

Keywords: Conceptual design, Maximum take-off weight, Regional Transport Aircraft, Constraint analysis

I. INTRODUCTION

This article focuses on the design point estimation of a regional turboprop transport aircraft based on a conceptual design process involving constraint analysis in order to carry out performance sizing. Aircraft conceptual design is the very first step in the design process starting with shaping an aircraft, studying and analyzing the constraints involved, and finalizing geometric details through aerodynamic considerations. It is an early activity that decides the preliminary development stage of an aircraft. This stage also involves the identification of the problem and the definition of a purpose in order to solve the potential problem. As the name indicates, the outcome of Conceptual design process is ideally a concept or configuration which necessarily does not provide the most accurate results but serves as the preliminary analysis for further detailed designing. The primary requirements for the basic design such as a specific new system comes into picture before shifting the focus into detailing. Recognition tends to initiate the aircraft's system conceptual design process to meet the necessary customer needs. During the conceptual design of the system, consideration is given simultaneously to both production and support. Results of the conceptual design along with past design results are consolidated in order to understand the feasibility. These results and system specifications are then delivered to the next phase, the preliminary design phase.

Regional networking plays a vital role in connecting communities, promoting economic growth, and fostering social development. One element in executing this connectivity is through stationing regional transport aircraft (RTA), built only to cater to the need of specific regional travel. RTAs are designed and manufactured to fill the gap between large commercial airliners and small general civil aviation aircraft. They easily help in connecting to smaller airports and remote locations with major transportation hubs. Civil passenger turbo-prop airplanes are used for passenger air travel at very cheaper prices than big aircraft. They usually arrive in between turbofan and turbo-jet aircraft. In the conceptual design process the specifications are carefully chosen, keeping in mind airliners requirements. The most important parameters like cruising speed, long range, and comfort of a passenger give an upper hand in this competitive world. The seating capacity of RTA varies from 30 to 100 with the extra weight of the cargo load. The initial pages of the report highlight the mission specifications given by customer, mission phases, description of similar RTAs, mission weight sizing and some important parameters for conceptual design.

II. MISSION SPECIFICATIONS

Any aircraft that is being developed has its mission specification given by customer or chosen from another developed aircraft. In our case the mission specifications are given by our customer. Mission specification of Mission profile is an important aspect that is taken into consideration during the conceptual design phase. Another important scenario where mission profile comes into picture is during the estimation of fuel weight where the fuel fractions for each segment of the mission must be determined.

Table 1 Mission Specifications of the Regional Transport Aircraft

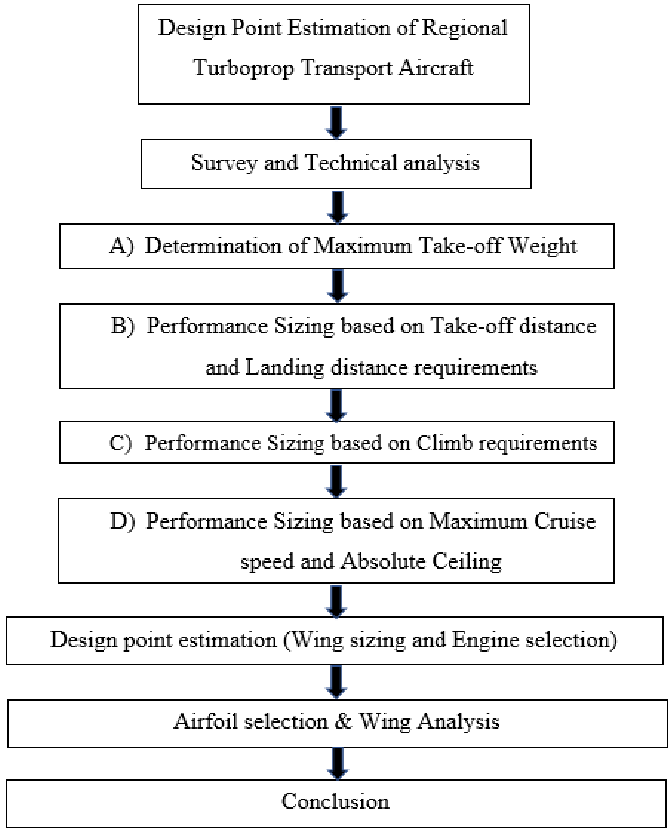
Payload	9550 kg
Passengers	90 passengers (90.8 kg each)
Crew	4 (including pilot) (90.8 kg each)
Cargo	1000 kg
Range	1500 km
Cruise Altitude	500 kmph
Service Ceiling	27000 feet (8229.6 m)
Take-off length	1500 m (4921.26 feet) at sea level
Landing length	1300 m (4265 feet) at sea level
Power plant	Two turboprops
Certification Base	FAR 25, FAR 23, EASA

III. THEORETICAL BACKGROUND

The process involved literature survey of various aircrafts and gathering information about the conceptual design phase.

- Define the survey objectives: Specific goals of the survey was determined such as gathering feedback on the design concept, assessing user preferences, or identifying potential improvements.
- Identifying customer needs: Based on the customer requirements, the design concept was altered and reframed.
- Collect and analyze responses: The survey response and statistical data was analyzed in order to identify the methodologies to be implemented and the areas of improvement.
- Interpret the findings: The survey results were interpreted and meaningful conclusions regarding the feasibility and viability of the conceptual aircraft design was drawn.
- A statistical study of various aircrafts was done by tabulating the operational empty weight and take-off weight. The tabulation and chart was made in order to understand the relationship of the ratio of operational empty weight and maximum take-off weight. A formulaic analysis was made which lead to the determination of maximum take-off weight of our aircraft.
- Performance sizing based on the customer requirements proved to be a crucial technique in the conceptual design phase. The take-off and landing distances were given by the customer, which was later utilized in formulaic analysis to lead us to four different curves for different coefficient of lift values.
- Performance sizing for climb requirements was based on six climb segments namely; Initial climb, Transition climb, Second climb, Enroute climb, Balked landing. Each segment had different characteristics based on FAR standards. Based on these characteristics, all six climb segments led to six different equations in terms of wing loading and power loading, which in turn gave rise to six different curves.
- Determination of design point and design space is done by combining the curves obtained due to performance sizing which in turn gives the wing area and power loading.
- Wing area is utilized to select the most suitable airfoil. Further, a 3-D model of wing is designed and structurally analyzed to deduce the intended results.

IV.METHODOLOGY



V. DESIGN POINT ESTIMATION

Design point is the region determined on a plot, where all the performance requirements of a considered domain (e.g. Engine performance) remains consistent. Set of equations involving temperature, pressure, volume of fuel consumed is analytically solved to determine the parameters involved under ambient and real time conditions. Design point estimation is the primary objective of the initial stage of conceptual design process.

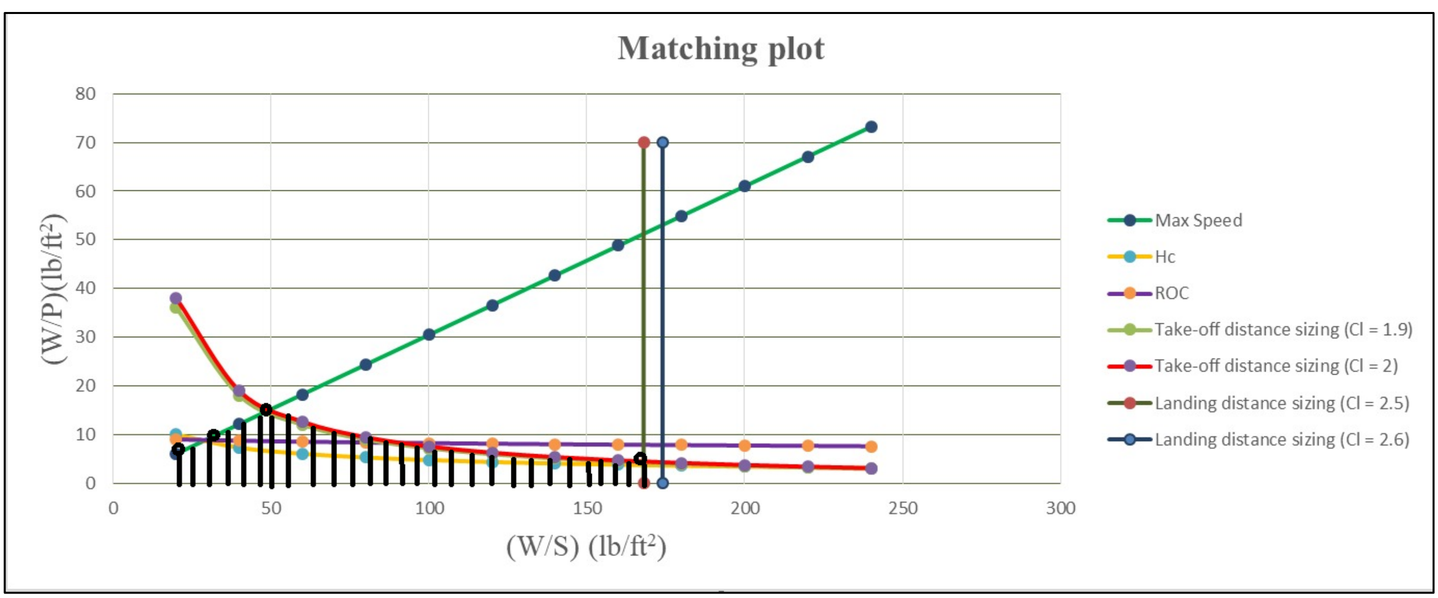


Fig 1 Matching Plot of Performance Sizing Curves

There are six steps to determine the wing area and engine power for propeller-driven aircraft:

- Derive one equation for each performance requirement such as Landing speed, Take-off run, Rate of Climb, etc. For propeller-driven aircraft, the equation is in the form of Wing loading (W/S) and Power Loading (W/S) functions.

- Sketch all the obtained curves in a graph where W/P is on the vertical axis and W/S is on the horizontal axis. Thus, plotting all the curves produces a variation of power loading to wing loading. The graph may intercept at many points and regions.

- There is an acceptable region formed in the graph which meets the requirements of aircraft performance. This region is referred to as design space. The design point is found in this design space.

- Determine the design point. The design point on the plot is one that yields the smallest engine terms in terms of power, which lies on the vertical axis.

- From the design point, we obtain the values of $(W/S)_d$ and $(W/P)_{d.}$

- Calculate the Wing reference area and Engine power from the above evaluation where the maximum take-off weight is also available. Further, the wing reference area is estimated by dividing the aircraft's maximum take-off weight upon wing loading. The engine power is calculated by dividing the aircraft takeoff weight by the power loading:

VI. AIRFOIL SELECTION

Airfoil selection directly affects the aerodynamic performance, aircraft handling qualities, stability and control. It is the second most devoted process after estimation of wing reference area. Airfoil section is responsible for the generation of the optimum pressure distribution on the top and bottom surfaces of the wing such that the required lift is created with the lowest aerodynamic cost.

Airfoil selection involves determination of a number of parameters before arriving at the most suitable type of airfoil for the regional transport aircraft. These include,

- Average Weight of the aircraft (W_{avg})
- Ideal Cruise Lift coefficient (C_{LC})
- Wing Cruise Lift coefficient (C_{LCW})
- Wing Airfoil Ideal Lift coefficient (C_{li})
- Wing Maximum Lift coefficient (C_{Lmax_w})
- Wing Airfoil Gross Maximum Lift coefficient (C_{Lmax_gross})
- Wing Airfoil Net Maximum Lift coefficient (C_{lmax})

The below table represents the list of parameters and their values.

Table 2 Airfoil Selection Parameters

Parameter	**Value**
Average Weight of the aircraft during cruise	27205.4 kgs
Ideal Cruise Lift coefficient	0.093
Wing Cruise Lift coefficient	0.097
Wing Airfoil Ideal Lift coefficient	0.108
Wing Maximum Lift coefficient	1.6842
Wing Airfoil Gross Maximum Lift coefficient	1.87
Wing Airfoil Net Maximum Lift coefficient	0.9713

Identification of the desired airfoil section is done based on the two lift coefficients; Wing Airfoil Net Maximum lift Coefficient (C_{lmax}) and ideal lift coefficient (C_{li}) whose values are 0.9713 and 0.108 respectively. Based on these values, from below figure, we can see that NACA 64-108 is the suitable airfoil. NACA 64-108 is an airfoil with maximum thickness 8% at 40% of chord and maximum camber 0.6% at 50% of chord.

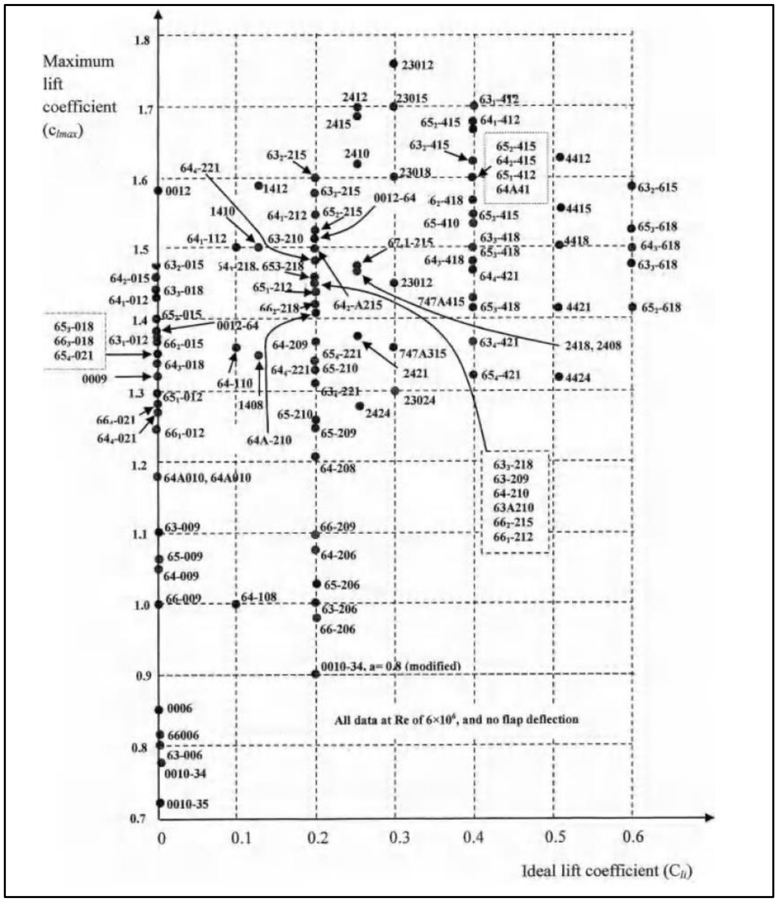


Fig 2 Maximum Lift Coefficient versus Ideal Lift Coefficient for Several NACA Airfoil Sections

VII. STRUCTURAL ANALYSIS OF WING

A 3-D Wing model using NACA 64-108 airfoil was designed as shown in the figure 3. A single wing was designed due to the symmetrical nature of the aircraft, thereby considering half wing span. The wing model was designed based on the following specifications:

Table 3 Wing Model Specifications

Aspect Ratio	12.8 m
Wing span	29.1 m
Mean Aerodynamic Chord	2.27 m
Taper Ratio	0.45
Root Chord	2.986 m
Tip Chord	1.34 m
Sweep Angle	3.24 deg
Rib, pieces	15
Rib thickness	1.016 mm
Web thickness	3.175 mm
Flange thickness	9.525 mm
Skin thickness	1.016 mm

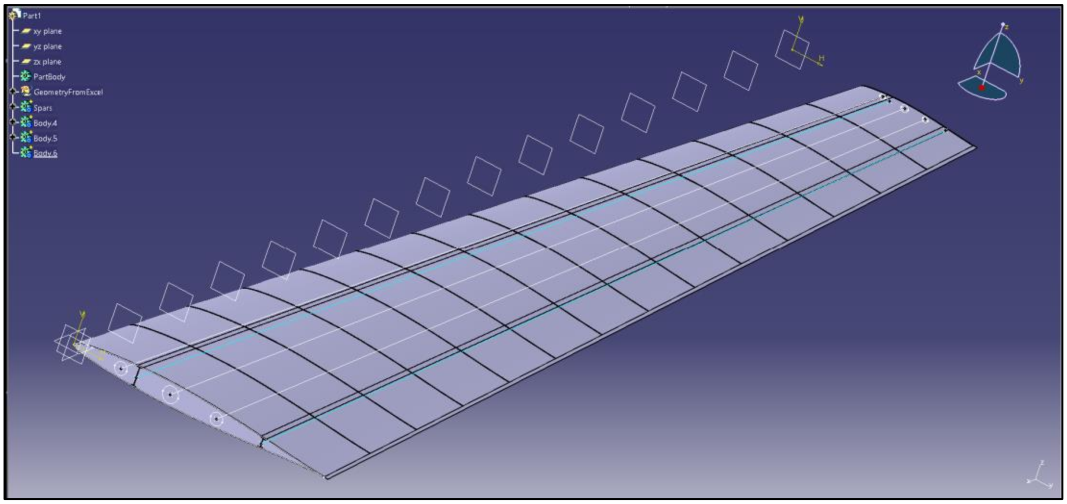


Fig 3 Isometric View of 3-D Wing Model

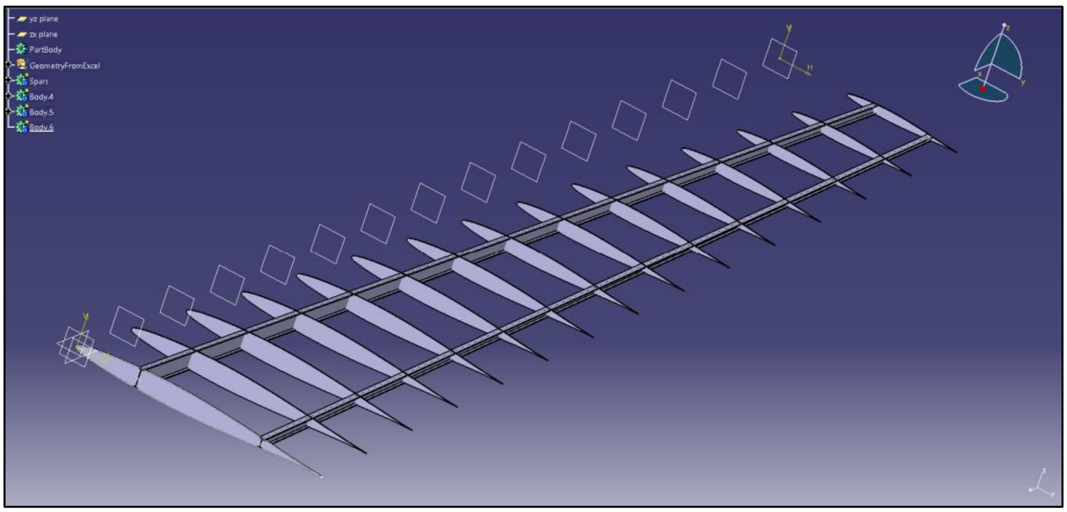


Fig 4 Isometric View of Ribs, Flanges and Web

During structural analysis, the material selected for the 3-D wing model is aluminium alloy. Properties of aluminium sheet is given below:

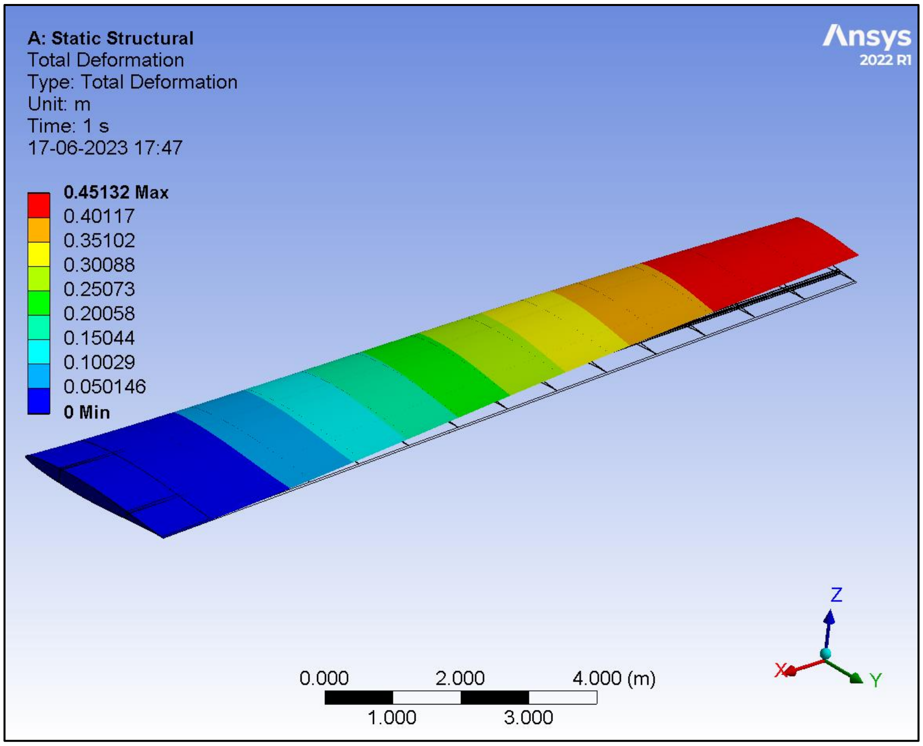
Table 3 Properties of Aluminium Sheet

Density	2809.51 kg/cm^3
Young's Modulus	68947.44 MPa
Poisson's Ratio	0.33
Yield Strength	441.264 MPa
Ultimate Tensile Strength	517.107 MPa

The structural analysis on the 3-D Wing model was carried out to estimate the responses in terms of strength and deformation, thereby validating the following objectives:

- Positive Maneuvering Limit Load Factor
- Wing Mass Estimation less than 12% of Maximum Take-off Weight
- Margin of Safety greater than 0.5

The solutions studied from the static structural analysis are represented in the following figure:



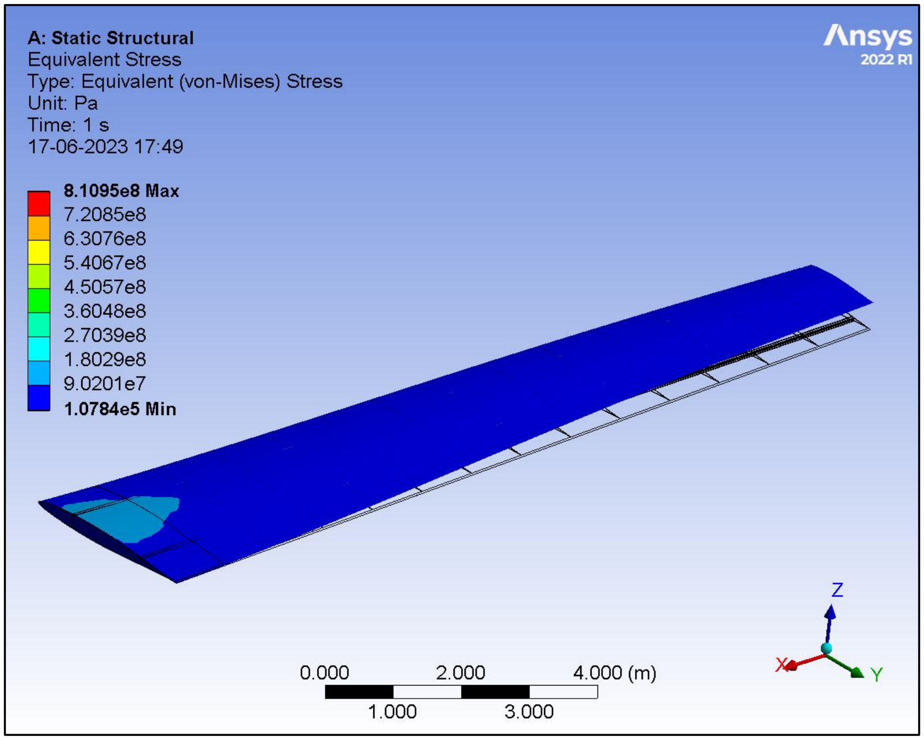


Fig 5 Total Deformation and Von Mises Stress of Wing Model

VIII. CONCLUSION

- To conclude, Design Point estimation proved to be a complex process involving several domains which include aerodynamics, propulsion, structures, and systems. Some major considerations and calculations had to be performed to estimate the optimal design point of the regional transport aircraft based on the mission specifications.

- The Design Space and Design Point has been estimated, using which we can determine the values of wing loading and power loading. These values can in turn can be used to calculate wing area and engine power. The definition of design point is the lowest point on graph corresponding to power loading which leads to low engine maintenance cost. Estimation of the optimal design point was carried out based on the assessment of the aircraft's cruise speed, stall speed, payload, range, and performance parameters.

- To arrive at the Design Point, estimation of the aircraft's maximum take-off weight and performance sizing were essential steps. Performance sizing led to respective performance curves which were reflected onto the matching plot to estimate the Design Point.

- The matching plot gave the corresponding values of wing loading and thrust loading which led to the calculation of wing reference area and power requirement. Based on the power requirement, the selection of an engine for the regional transport aircraft was done.

- NACA 64-108 was selected as the most suitable airfoil for the aircraft. Further, design and analysis of 3-D Model of wing was carried out.

- Results drawn from the work carried out can be represented as follows:

Maximum Take-off Weight	38540.43 kgs
Wing Loading (from design point)	582.131 kg/m^2
Power Loading (from design point)	4.257 kg/kW
Wing Reference Area	66.20 m^2
Engine Thrust	9051.41 kW
Engine Selected	PW150A Canada
Maximum Total Deformation	0.4513 m
Mass of Single Wing Structure	530 kgs
Minimum Safety Factor	0.544
Load Factor	1.838
Margin of Safety	0.838

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