# BAE-4
# STOL Cargo Plane


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# Abstract

In this project, we present a wing design for a cargo aircraft with propeller engine. The wing is optimized for a specific task with medium length runway, short range and high climb rate requirements. We employ a rectangular wing design with airfoil NACA23015 considering the practicality of manufacturing, cost reduction and maintenance. The nose up on the ground, incidence angle and flap are used to increase its performance. The wing configurations and fly conditions are designed separately for takeoff phase, climb phase and cruise phase to fully utilize the wing capability. A aerodynamic analysis is conducted with XFLR5 and MATLAB. Panel method is used for 2D airfoil analysis and vortex panel method is used for 3D wing analysis. The analysis shows that the requirement of the task can be fully satisfied by our design with high performance.

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# 1 Introduction

Improving the aerodynamics performance of the wing is one of the major approach to attain the desired performance of a aircraft. The design and optimization of the wing requires adjustment of various coefficients with complex effect on the aircraft capability. For current task, the optimization of the wing is conducted to improve the performance of the aircraft by maximizing the payload capacity subject to constrains of minimum range, maximum deliver time, maximum take-off length and minimum climb rate. In our design, a rectangular wing with NACA 23015 airfoil is used, which makes construction of the wing simpler and cost efficient. We are also considering the dihedral angle of 7° which can improve the lateral stability of the aircraft. Flaps being hinged to the aircraft wing are additional wing configurations which helps in improving the maximum takeoff weight at low speeds. The design parameters of the wing are adjusted to increase the aerodynamic performance based upon the XFLR5 aerodynamic analysis. The performance evaluation and the constraint verification based on the results from the analysis are done using MATLAB. The adjustment and verification process goes iteratively considering the takeoff phase, climb phase and cruise phase comprehensively till convergence to get a valid design. The maximum possible performance among the valid designs. The best performance is achieved with the aforementioned characters.

## 1.1 Performance Evaluation

The purpose of the project is to achieve the best possible performance of the aircraft under given constraints such as range, maximum flight time, minimum climb rate, maximum take-off length and the engine power. In order to achieve this performance, a wing of a particular configuration is designed and optimized accordingly by considering the suitable data assumptions. The desired performance is a function of the maximum amount of payload the aircraft can carry with a minimum rate of fuel consumption and deliver time, which is evaluated as follows:

$$\mathrm{P} = \left(\frac{\text{payload (kg)}}{1000} + \frac{\text{payload}}{\text{fuel (kg)}}\right) \times \frac{1500}{\text{flight time (hr)}}$$

## 1.2 Project Constraints

The wing design process is subjected to certain constraints which must be satisfied by the cargo plane. Table 1 shows the major constraints which should be considered during the design process. The stall speed is calculated from equation1. Takeoff length is estimated by equation 2. the density of the air at sea level is $\rho = 1.225\text{kg/m}^3$, the density of the air at at 3000 m altitude is $\rho = 0.9093\text{kg/m}^3$.

Table 1: Flight constraints.

| Constraint | Description |
|---|---|
| Range | 1500 km at a cruising altitude of 3000 m |
| Flight time | Maximum 5 hours |
| Sea level rate of climb | 6 m/s |
| Sea level takeoff length | Maximum 550 m |
| Takeoff speed | At least 20% more than stall speed |
| Engine power | 400 kW |

$$V = \sqrt{\frac{2mg}{\rho C_{Lmax} S}} \tag{1}$$

$$L = 2.34 \frac{m^2 g}{S C_{Lmax} T} \tag{2}$$

## 1.3 Data Assumption

The following are the assumptions considered in the design of the wing to obtain the desired maximum performance of the aircraft.

1. The empty weight of the aircraft is assumed to be half of the total take-off weight. Thus it equals to the combined weight of the fuel and payload of the aircraft. i.e.

   $$\text{Empty weight} = (\text{Payload} + \text{fuel weight}) = 0.5 \times (\text{Total Takeoff weight})$$

2. Parasite drag of the fuselage and tail is equal to the parasite drag of the entire wing in the cruise stage.

3. The fuel consumption rate of the aircraft is proportional to the required power to be generated by the engine. The specific fuel consumption rate for the aircraft engine is 0.38 kg/kW*hr. The specific gravity of the aviation fuel is taken as 0.8.

4. The overall range of 1500 km is divided in three segments of 500 km to consider the effect of fuel consumption. Thus the mass of fuel consumed for the overall cruising segment is evaluated in three individual 500 km segments. The overall weight of the aircraft decreases continuously as the flight cruises and it results in the reduction of the required engine power and in the fuel consumption rate.

   $$m_{\text{fuel}} = c \cdot P_i \cdot \frac{R_i}{V_i}$$

5. The volume of the fuel tank is assumed to be 40% of the total wing volume.

6. The takeoff speed of the airplane is taken as the 1.2 times the stall speed at takeoff.

# 2 Design

## 2.1 Airfoil Design

Begin with the publication of the NACA report *The Characteristics of 78 Related Airfoil Section from Tests in the Variable Density Wind Tunnel* at 1930s [1], the NACA airfoil series changes the rather arbitrary airfoil design process and provides excellent references. After the development of over a half century, now it contains a series of successful designs employing advanced theories and techniques. Among all those series, the NACA four-digit series and five-digit series are the earliest airfoil series. Both give a full geometric description by its digits. For its simplicity and generality, those two series have been wildly used for various aircraft designs. For current task, in which a small cargo plane cruise at low speed, the main bottle neck is the takeoff weight rather than the stall behavior. Compared to NACA 4-digit series, NACA 5-digit series have higher maximum lift coefficient, which benefits the design. The worse stall behavior, which is less important in current task, and been proved far from the fly condition in our design, is ignored.

For NACA 5-degit series, the first digit, when multiplied by 1.5, represents the design lift coefficient. The second and third digits, when divided by 2, represent the position of the maximum camber in percentage chord. The final two digits represent the maximum thickness of the airfoil. A series of airfoils in NACA 5-digit series has been tested at the takeoff stage, in which $Re \approx 5,000,000$ and angle of attack 12°. The results are listed in the following table. NACA23015 has good performance in both lift $C_l$ and $C_l/C_d$. So we select NACA 23015 for the wing design and optimization.

Table 2: Performance of NACA 5-digit series at takeoff stage

| Airfoil | $C_l$ | $C_d$ | $C_l/C_d$ |
|---|---|---|---|
| NACA 23015 | 1.475 | 0.011 | 137.927 |
| NACA 23017 | 1.470 | 0.011 | 139.445 |
| NACA 23007 | 1.411 | 0.015 | 96.199 |
| NACA 13015 | 1.284 | 0.016 | 80.242 |
| NACA 33015 | 1.290 | 0.015 | 87.340 |
| NACA 24015 | 1.479 | 0.012 | 129.084 |
| NACA 22015 | 1.455 | 0.011 | 136.836 |

## 2.2 Wing Design

For the wing design, we started with a rectangular wing. The wing area is optimized to maximize the lift and payload while keeping the climb speed above the required velocity. Increasing the aspect ratio helps in amplifying the lift coefficient. But it should be kept in a reasonable value. To be practical, current design is close to the typical case of cargo planes. Trapezoid wing has a better performance then the rectangular wing. However, considering the increment of the cost in manufacturing, and the size of the plane, it is not used in our final design. Washout is not included for the similar reason. The main bottle neck of the design is the maximum takeoff weight in the takeoff phase. We use flaps to overcome this limitation and boost the performance. With all these considerations, comes our current wing design.

# 3 Configuration

## 3.1 Wing

The wing has a constant chord of 1.8 m and a span of 16 m. The wing area is 28.8 and the aspect ratio is 8.89. There is a constant dihedral of 7 degrees without any sweep or twist. Also, the wing is installed on the airplane body at an angle of 3 degrees. Using flaps reduces the takeoff length which is what we want. Our wing has two sets of flaps, trailing edge flaps as wide as 50% of the span and leading edge flaps over the whole span. The wing configuration can be seen in figure 1. The trailing edge flap starts at 75% chord with the hinge on the camber line. The leading edge flap starts at 20% chord with the hinge on the camber line, as well. The wing has a constant cross section of NACA 23015. This airfoil at 1.8 m chord has an area of 0.1021 $m^2$. As a result, the total volume of the wing is 1.6336 $m^3$. The stall angle of attack of this wing is at about 20 degrees. However, in every stage of our flight mission, the plane flies at much lower angles of attack. This rectangular wing is very practical in a manufacturing point of view. The standard NACA 23015 section airfoil will make life much easier on the people that are going to actually build this wing. Rectangular wings are not uncommon in today's aircraft configuration, especially in short takeoff length cargo planes.

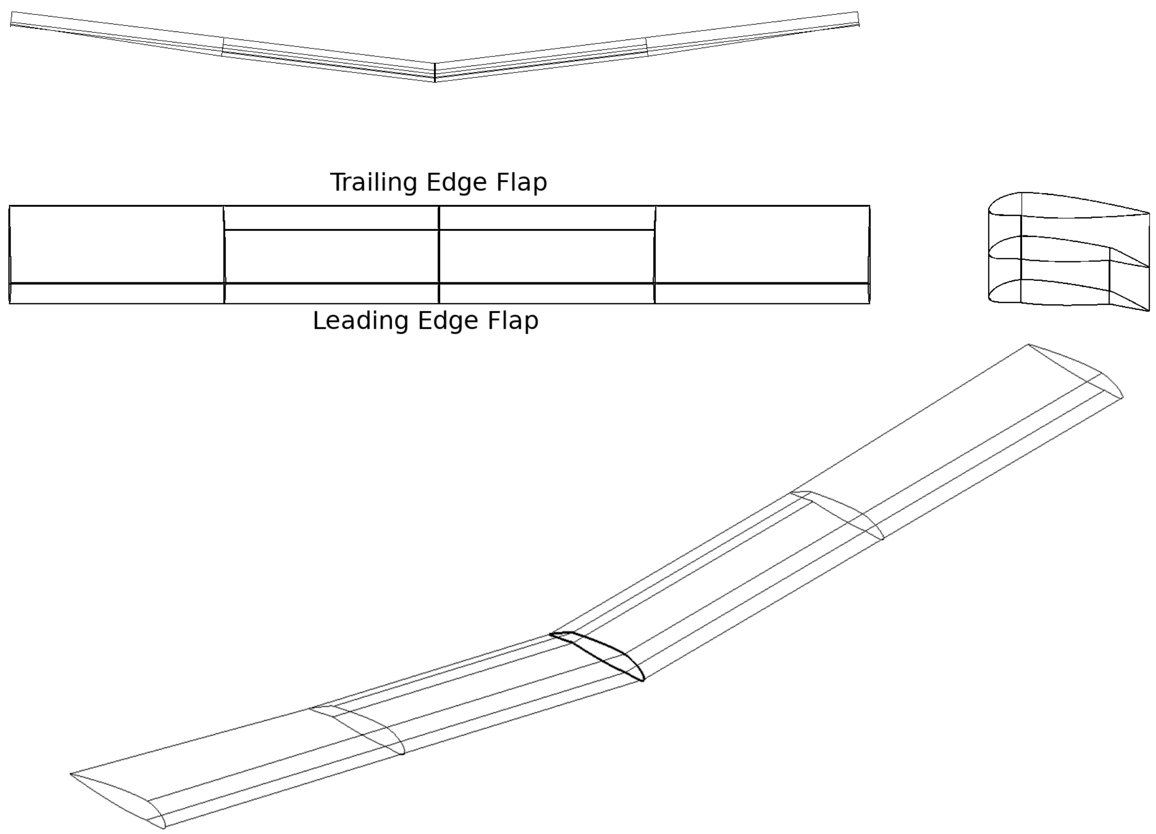


Figure 1: Wing configuration.

## 3.2 Landing Gear

Our aircraft uses a conventional landing gear (tailwheel type landing gear) which consists of two main wheels forward of the center of gravity and a small wheel or skid to support the tail. In this configuration our airplane has 10 degrees nose up while on the ground. The tailwheel configuration offers several advantages over the tricycle landing gear arrangement, which make tailwheel aircraft less expensive to manufacture and maintain. Other advantages of such configuration include:

- Due to its position much further from the center of gravity, a tailwheel supports a smaller part of the aircraft's weight allowing it to be made much smaller and lighter than a nosewheel. This small wheel causes less parasitic drag.
- Because of the way airframe loads are distributed while operating on rough ground, tailwheel aircraft are better able to sustain this type of use over a long period of time, without cumulative airframe damage occurring.
- If a tailwheel fails on landing, the damage to the aircraft will be minimal. This is not the case in the event of a nosewheel failure, which usually results in a prop strike.

- Due to the increased propeller clearance on tailwheel aircraft less stone chip damage will result from operating a conventional geared aircraft on rough or gravel airstrips, making them well suited to bush flying.
- More suitable for operation on skis.
- Eeasier to fit into and maneuver inside some hangars.

Conventional landing gear arrangement has the following disadvantages compared to nose wheel aircrafts:

- Tailwheel aircraft are more subject to "nose-over" accidents due to injudicious application of brakes by the pilot.
- Conventional geared aircraft are much more susceptible to ground looping.
- They generally suffer from poor forward visibility on the ground, compared to nose wheel aircraft.
- More difficult to taxi during high wind conditions, due to the higher angle of attack on the wings which can then develop more lift on one side, making control difficult or impossible.

# 4 Wing Analysis

In this section the detailed analysis of our wing design is presented. The LLT method of wing analysis in XFLR5 is utilized for this purpose. The lift coefficient distribution at three stages of flight is presented in figure 2. Our cruise is at constant velocity which makes the lift distribution for three sections on cruise pretty similar. As seen in this figure, the lift required for takeoff is the highest. Also, at cruise flight not much lift is required. in our desing a key feature is the drag at cruise flight. our cruise flight is at about -0.247 degrees angle of attack which accounts for a very low amount of parasite and induced drag. The parasite drag distribution over the span of the wing for the stages of flight are presented in figure 3. Also, the induced drag distribution is presented in figure 4. As you can see in these figures, both drags are much less at cruise flight than the other stages. This means a very low power required fro flight and low fuel consumption. The induced drag distribution at cruise is constant which is also a plus. Parasite drag at takeoff is highest and about constant from root to 50% of span This is due to the presence of flap at 15 degrees. The total lift coefficient is plotted vs. total drag coefficient of the wing for all three stages in figure 5. As seen in this figure, we only use a very small range of lift and drag coefficients for takeoff phase. Our XFLR5 analysis is conducted at constant angle of attack for takeoff phase, constant lift for climb phase, and constant velocity for cruise phase. Figure 6 shows the performance of the wing in different stages in form of the lift over drag curve. As seen in this figure, cruise configuration generates the maximum lift over drag at 0 degrees angle of attack. This is a very important consideration as we are also flying the cruise stage at about 0 degrees angle of attack. This means better performance at 0 angle of attack with less drag which accounts for minimum fuel consumption.

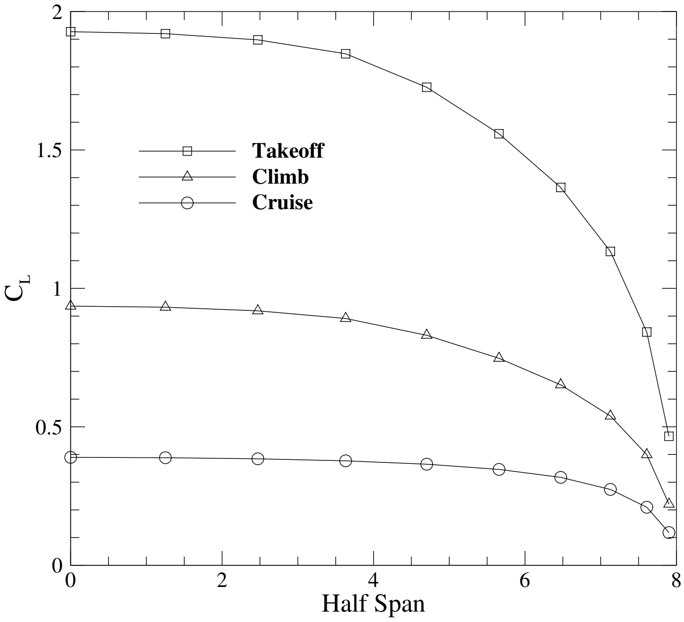


Figure 2: Lift coefficient distribution at three stages of flight.

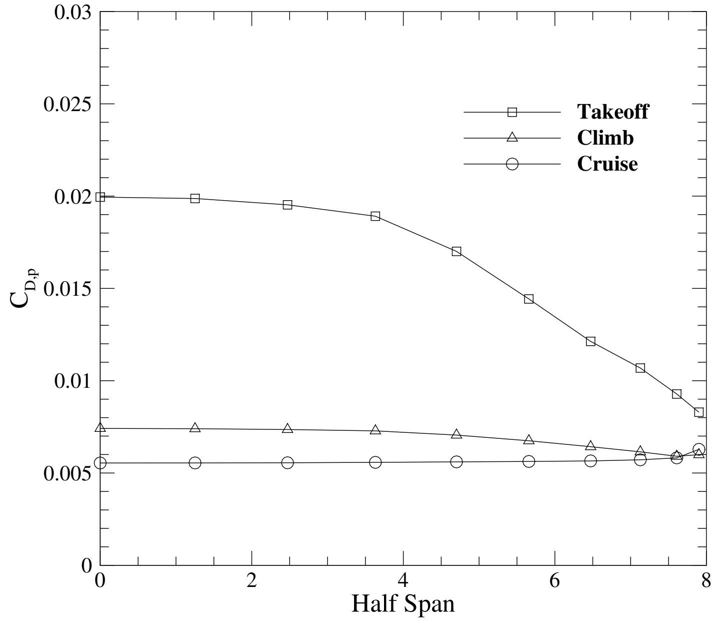


Figure 3: Parasite drag coefficient distribution at three stages of flight.

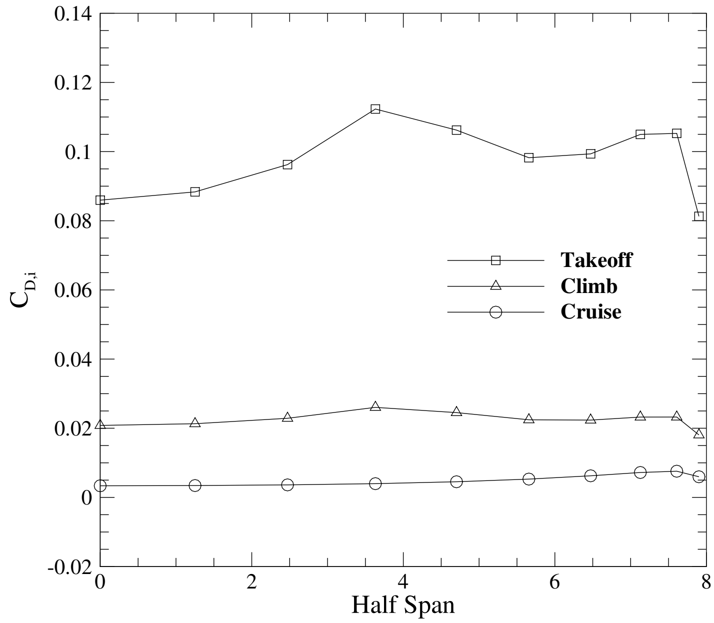


Figure 4: Induced drag coefficient distribution at three stages of flight.

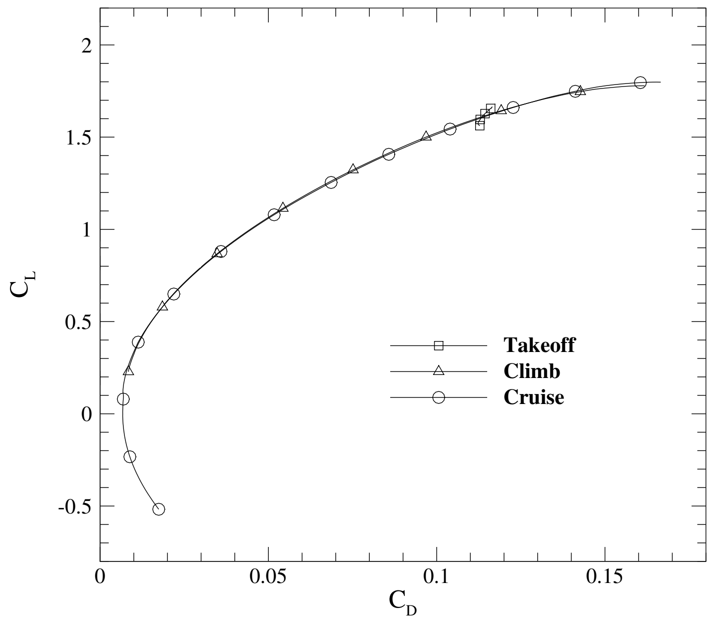


Figure 5: Drag polar of three stages in the flight envelope

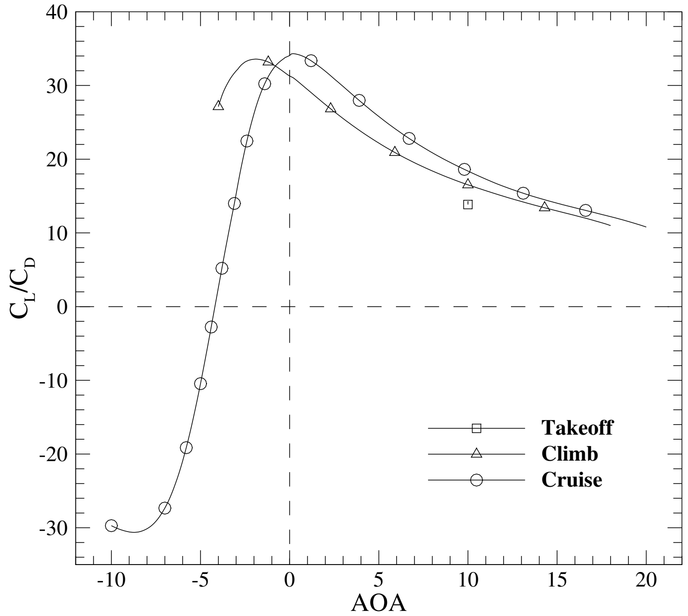


Figure 6: Lift over drag at different stages of flight

# 5 Flight Envelope and Performance

This airplane and its mission are designed for the maximum performance possible. The flight mission is sketched in figure 7. As seen in this figure, the airplane starts the mission with taxi to the beginning of the runway. Then, it will takeoff at full power. Next phase is climb to a height of 3000 meters which is also at full power. After that, it will cruise for 1500 km at constant speed of 306 km/h. Then, it will descent and land at the destination. The flight specifications at each stage are presented in the following sections.

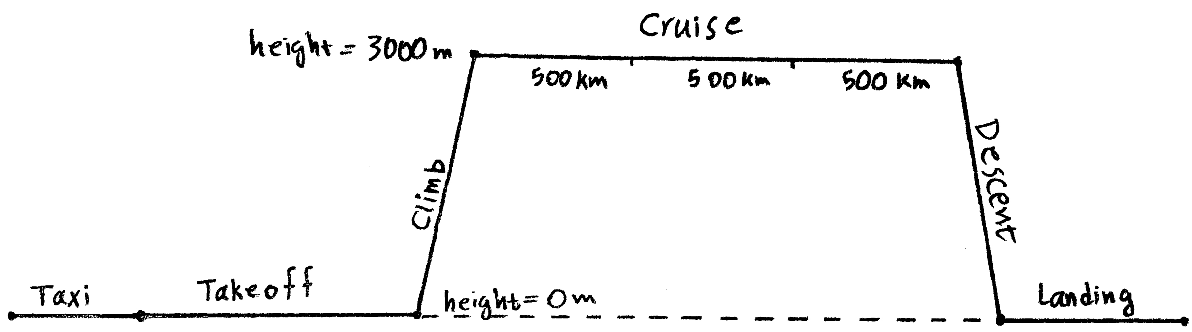


Figure 7: Flight envelope.

## 5.1 Takeoff Phase

This stage of the flight mission is the most important one. We need to takeoff as much weight as possible, off the ground. In our XFLR5 analysis, we have not considered the ground effect and have used LLT analysis. The airplane with tailwheel-type landing gear configuration has a nose up angle of 10 degree on the ground. The XFLR5 analysis for this stage is at constant angle of attack of 10 degrees. The leading edge and trailing edge flaps are set to 10 and 15 degrees, respectively. Takeoff airspeed is 40.4061 m/s which generates a lift coefficient of 1.64347. Maximum takeoff weight in this configuration is 3350.6 kg and as a result stall speed is 33.6717 m/s and takeoff length is exactly 550 m. The takeoff airspeed is 20% more than the stall speed. Table 3 summarizes the flight parameters at this stage of the flight.

Table 3: Flight parameters at takeoff.

| Parameter | Value |
|---|---|
| Stall velocity [m/s] | 33.6717 |
| Takeoff velocity [m/s] | 40.4061 |
| Takeoff Vel./Stall Vel. | 1.2 |
| Max takeoff weight [kg] | 3350.6028 |
| Takeoff length [m] | 550 |
| Lift coefficient | 1.64347 |
| Induced drag coefficient | 0.098795 |
| Parasite drag coefficient | 0.032963 |

## 5.2 Climb Phase

We have to design the mission in a way that we get a climb rate of over 6 m/s. Also, the fuel consumption for this stage is considered as a percentage of the consumed fuel at cruise. This stage of the flight is analyzed in XFLR5 for a constant lift with the maximum takeoff weight. The leading edge and trailing edge flaps are set to 0 and 5 degrees, respectively. Our airplane has a climb rate of 7.5046 m/s immediately after takeoff. At full power the nominal climb rate is designed to be 9.9196 m/s which can be reached at an airspeed of 48.4873 m/s and angle of attack of 2.4305 degrees. At 68% of the full power, we will get a climb rate of 6 m/s. Table 4 summarizes the flight parameters at this stage of the flight.

Table 4: Flight parameters at climb.

| Parameter | Value |
|---|---|
| Climb rate at takeoff [m/s] | 7.5046 |
| Nominal climb rate at full power [m/s] | 9.9196 |
| Nominal climb rate at 67.79% of full power [m/s] | 6.0 |
| Air speed [m/s] | 48.4873 |
| Angle of attack [degrees] | 2.4305 |
| Lift coefficient | 0.79259 |
| Induced drag coefficient | 0.02285 |
| Parasite drag coefficient | 0.013924 |

## 5.3 Cruise Phase

Cruise speed is kept constant at 306 km/h. As a result, the XFLR5 analysis for this stage is conducted at a fixed velocity of 85 m/s. Both the leading edge and trailing edge flaps are set to zero in this stage of the flight. The airplane will travel 1500 km in 4 hours and 54 minutes. This stage is divided into three sections of 500 km. at the beginning of each section the consumed fuel from last section is deducted from the airplane weight. It should be mentioned that the cruise phase starts with the maximum takeoff weight. The consumed fuel in the cruise flight is 235.4366 kg. Table 5 summarizes the flight parameters at this stage of the flight.

Table 5: Flight parameters at cruise.

| Parameter | Value |
|---|---|
| **Sector 1** | |
| Cruise velocity [km/h] | 306 |
| Flight time [h] | 1.63 |
| Consumed fuel weight [kg] | 79.3827 |
| Power/full power [%] | 31.96 |
| Lift coefficient | 0.34744 |
| Induced drag coefficient | 0.004678 |
| Parasite drag coefficient | 0.011221 |
| **Sector 2** | |
| Cruise velocity [km/h] | 306 |
| Flight time [h] | 1.63 |
| Consumed fuel weight [kg] | 78.47 |
| Power/full power [%] | 31.59 |
| Lift coefficient | 0.33921 |
| Induced drag coefficient | 0.004460 |
| Parasite drag coefficient | 0.011257 |
| **Sector 3** | |
| Cruise velocity [km/h] | 306 |
| Flight time [h] | 1.63 |
| Consumed fuel weight [kg] | 77.58 |
| Power/full power [%] | 31.24 |
| Lift coefficient | 0.33107 |
| Induced drag coefficient | 0.004250 |
| Parasite drag coefficient | 0.011288 |
| **Overall** | |
| Flight time [h] | 4.902 |
| Consumed fuel weight [kg] | 235.44 |

## 5.4 Fuel Volume

The airplane wing has a volume of 1.6336 $m^3$. Further, we need to load 35% more fuel than we need for the cruise phase. This means that the maximum fuel weight is 317.7839 kg which has a volume of 0.40386 $m^3$. This is about 25% of the wing volume.

### 5.5 Performance

The aircraft performance with the current configuration is 1722.2805, which is a good number. The performance parameters are presented in table 6.

Table 6: Performance parameters.

| Parameter | Value |
|---|---|
| Max. Payload [kg] | 1357.462 |
| Max. Fuel [kg] | 317.8394 |
| Flight Time [h] | 4.902 |
| Performance | 1722.2805 |

# 6 Conclusion

The project presents the design of the wing for a single-engine propeller-driven cargo plane intended for short-distance cargo delivery. The rectangular wing with constant section of NACA 23015 airfoil is used for this plane. The airplane is designed to cruise at 306 km/h, as a result the range of 1500 km can be covered in 4 hours and 54 minutes. The flaps are mounted on the wing at the leading and trailing edges to increase the lift during the takeoff and climb phases which enables us to carry maximum payload of 1357 kg. The maximum amount of fuel needed to carry for this mission is 318 kg which occupies 25% of the wing volume. The minimum rate of climb of 6 m/s is obtained during the climb phase by just using 68% of engine power while the rate of climb of 9.92 m/s can be achieved by running the engine at full power. The maximum performance of 1722 is achieved with this design while satisfying all the constraints.

# References

[1] E. N. Jacobs, K. E. Ward, and R. M. Pinkerton, "The characteristics of 78 related airfoil sections from tests in the variable-density wind tunnel," 1933.