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Design, Analysis and Development of an Ornithopter

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Abstract—**In recent years the subject of flying vehicle propelled by flapping wings, also known as ornithopter, has been an area of interest because of its application to micro aerial vehicles (MAVs). These miniature vehicles seek to mimic small birds and insects to achieve never before seen agility in flight. This renewed interest has raised a host of new problems in vehicle dynamics and control to explore. Ornithopters are robotic flight vehicles that employ flapping wings to generate lift and thrust forces. In order to better study the control of flapping wing flight we are developing an ornithopter model which will be capable of carrying a wireless camera. This report elaborates the essential aspects for the development of ornithopter and also describes mechanism of operation and the various applications of our ornithopter model. Our ornithopter model has a wing-span of 1.15m with a constant flapping frequency of 3Hz. The design for the same model is done with the objective of achieving the maximum lift and minimum drag possible which are the most important aspects considering the flight of the ornithopter. The complete design of the ornithopter model is done in SOLIDWORKS. The Ornithopter model is developed by keeping the aspects of gear reduction, aspect ratio, importance of tail, centre of mass, power requirements in consideration. At last, the design was analysed using CFD in ANSYS FLUENT in order to get the results of lift and drag force at various angle of attack and flow velocities.**

Keywords**— Ornithopter, flapping wings, CFD, Lift, Drag**

I. Introduction

An **Ornithopter** is an aircraft that flies by flapping its wings. It is an imitation of birds. Since time immemorial, flying in the sky has been a source of fascination to most humans. Birds have long inspired human flight. And thus, there had been various attempts by mankind to achieve flight and take to the skies. Fixed winged aircrafts normally employ wings only to generate the lift required to sustain in the air. These have disadvantages in terms of speed, efficiency and manoeuvrability. Additionally, the advantages of an Ornithopter are more relevant at small scales, where, unfortunately, incorporating the flapping wing features is mechanically more of a challenge. Some of the advantages of a flapping-wing aircraft are as follows:

- Lift and thrust are created through the same mechanism. This eliminates the requirement of rotors or propellers or any other separate mechanism to create propulsive force.
- Since no rotors are required, Ornithopters are lighter and quieter.
- Excellent maneuvering capabilities, ability to fly at very low as well as relatively high speeds.

II. Objectives

The objective of this project is to:

- To study the flying mechanism of a Bird.
- Analyze the parameters important for the flight of a Bird.
- To get the desired specification of the ornithopter.
- Design the model of Ornithopter according to parameters.
- Analyze the model and get the effect of various parameters on it.
- To study the analysis of Ornithopter and its effect

III. Design of Ornithopter

While designing an ornithopter first of all we have to select flapping frequency according to predicted weight. From various experimental studies Wing Frequencies were observed and on the basis of the analysis following equation was used to show that wing frequency(f) may be estimated by:

$$f = m * g * b * S * \rho$$

where m is the bird's body mass, g is the acceleration due to gravity, b is the wing span, S is the wing area and ρ is the air density.

As per our ornithopter model, we have following values of the parameters:

Parameters	Symbol	Value	Unit
Bird's body mass	m	0.45	kg
Acceleration due to gravity	g	9.81	m/s^2
Wing span	b	1.146	m
Wing area	S	0.46	m^2
Air density	ρ	1.225	kg/m^3
Wing flapping frequency	*f*	2.86	Hz

TABLE I. FLAPPING FREQUENCY CALCULATION PARAMETERS

A) Gear box: Spur gearbox

The most critical part of the ornithopter is the drive mechanism that converts the electric power from the battery to the flapping motion of the wings. This system is the most complex to design and fabricate because it must withstand very large forces that reverses direction several times a second while at the same time it needs to be extremely light and durable. Because of the loads, it must be made from durable material which makes it beneficial to perform careful analysis and trim as much weight as possible. The drive system can be further broken down into four sections, the electric motor, a gear reduction stage, a linkage to convert the high torque rotation into a reciprocating motion and the connection to the wing spars.

Spur gears feature a simple, compact design that makes them easy to design and install, even in limited or restricted spaces. These gears increase or decrease shaft speed with a high degree of precision at a constant velocity.

While a highly integrated design is needed in order to maximize the power to weight ratio, the analysis of these parts breaks down well, gear reduction for outer runner motor having specification speed of motor 8350 RPM should be,

$$Flapping\ Frequency = \frac{Motor\ Load\ Speed}{Gear\ Ratio}$$

The gear reduction should be 32. Which means while the motor rotates 32 times the main gear rotates once. This also reduces the torque needed for the motor. Less torque motor means a reduction in motor size and weight.

Accordingly, calculations were done and specifications of required gears were obtained, as specified in the following table,

.

GEAR NO.	PITCH CIRCLE DIAMETER	NO. OF TEETH	MODULE	QUANTITY
1	10	10	1	3
2	20	20	1	3
3	40	40	1	2

TABLE II. SPECIFICATION OF GEARS

The gear box design is done in SOLIDWORKS and these gears were assembled on two base plates for supporting them. The shafts used were 5mm mild steel shafts with push fit. For flapping motion of wing, we select simple a four-bar mechanism inversion (Dual Crank mechanism) which is strong for sustaining the large force and connecting rod should have some flexibility so for that tie rod is the best option.

1) Material Selection for Components of Gearbox:

- Motor pinion – Mild steel
- Other gears – Nylon
- Shaft – Steel
- Crank and connecting rod – Carbon fibre

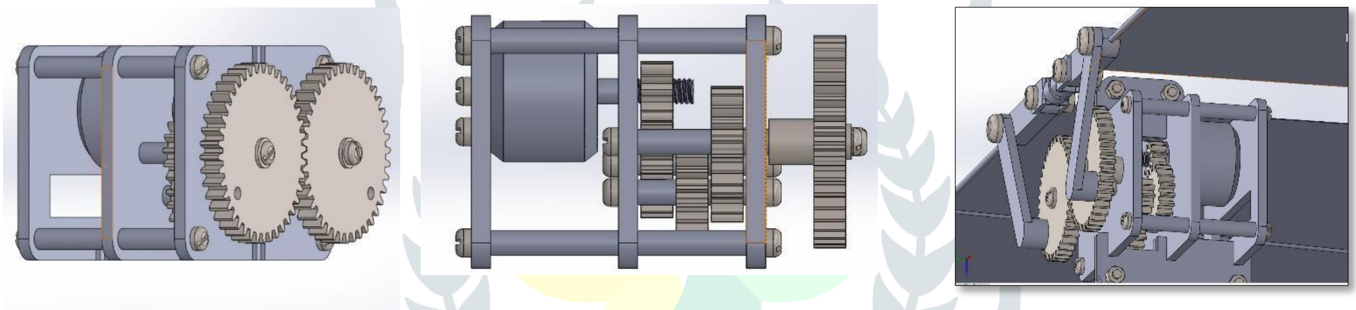


FIG. I GEARBOX ASSEMBLY

B) Flapping mechanism: Dual Gear Crank mechanism

The flapping wing mechanism function is to convert the motor's rotary motion into flapping motion. It is the most important component of the ornithopter thus much research was done to assess the many different designs available. Generally, the mechanism design is about the same to each other with only slight modifications.

This design features two gears that control each wing hinges separately. A simulation test was done using the Ansys and it showed that it could hold at high frequency flapping and the flapping movement is synchronized.

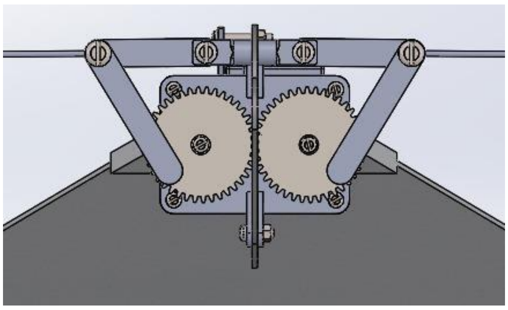


FIG. II DUAL GEAR CRANK MECHANISM

C) Wing:

Design: Flexible wing

Ornithopter wings can be flexible or rigid. The rigid wing design is much more complicated. Each cross section of the rigid wing has a real aviation wing profile. These wings require a frame system and accurate geometry. Furthermore, ornithopter with a rigid wing is bigger and heavier which is complicated to make. So, we decided to keep the wings of our ornithopter flexible. Flexible wings are like a stretched fabric that forms a membrane made from lightweight, tear-resistant material. Also, the material must not allow to pass air through. The membrane wing consists of a spar, at the leading edge of the wing and a wing membrane which extends backward from the spar and attaches to the body of the ornithopter. The rigid structure is concentrated at the front of the wing. The same is seen in case of birds, bats, pterosaurs, and most insects. During flapping, the more flexible membrane portion of the wing will passively lag behind the rigid wing spar. We refer to this as "Twisting" of the wings. It is important because it keeps the wing adjusted to the correct angle for both the upstroke and the downstroke. To improve the lift of basic membrane wing, some diagonal brace to the wing structure is also added.

The process for calculating specifications can be seen in the section below.
First, the constants were set.
Coefficient of Drag (C_d) = 0.189
Density of air (**ρ**) = 1.225 kg/m3
Acceleration due to gravity (G) = 9.81 m/s2
Maximum angle wing makes concerning the body (θ) = 1.2217 radians
The coefficient of drag was set as if the wing was a flat plate. This was done because the velocity
of the wing is in the Y direction concerning the direction of the travel of Wing. Also, the surface area of the wing when looking straight at Wing's beak produces negligible drag. Therefore, the only source of drag will come from this flapping motion.
Finally, values were calculated, Considering

Wing Span (b) = 1.146 meter
Chord Length (c) = 0.224 meter
Initial Weight of Bird = 0.45 kg

1) Drag Force (F_d) was Calculated with the following equation:
$F_d = (\rho * C_d * c * b^3)/3$
2) Angular Momentum (ω) was Calculated using the following equation:
$\omega = (M * G/F_d)^{1/2}$
3) The Torque (r) Of the Wings was then calculated:
$r = (\rho * \omega 2 * Cd * c * b4)/8$
4) Power (P) In Watts was calculated:
$P = r * \omega$
With the help of above standard equations, the drag force is calculated as 0.026 N, Angular
momentum obtained is 14.402 rad/s, the value for the torque of wings is 2.31 N-m and the power required is 33.26 watts. Since the power of the available motor is 280 watts, the designed wings can withstand the drag force and the ornithopter can fly easily. The parameter for wings is now decided so the second most important thing is to provide proper support to wings. Support is a crucial part of wing design and needs to be provided so that the wing membrane won't get torn off. In this support structure, the spar is the part where all forces reaction gets transmitted.
For spars, we require high rigidity and stiffness where for membrane we require high tensile strength with less weight.

Material selection for wing:

- Spar – Carbon Fiber
- Membrane – Nylon Fabric

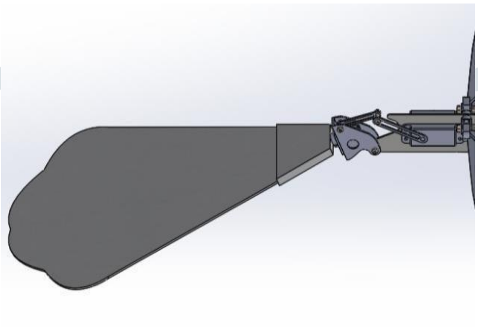
D) Tail

Steering is usually done by the tail. The wings can be used for steering, but this is less consistently successful and more difficult to implement. A simple elevator and rudder system is very effective for ornithopter steering. For a more birdlike appearance, though, a flat, triangular tail is more often used. The tail may swing out to the left and right sides so that the downforce of the tail causes a rolling moment on the ornithopter. Alternatively, the tail may rotate about its long axis. In this case, the downforce is redirected in a way that provides yaw control. Flat v shape design is used since it is consistently successful [6].

Material selection for the tail:

- Spar – Carbon Fiber
- Membrane – Nylon Fabric

FIG. III TAIL MECHANISM



E) Main Frame

The mainframe of the ornithopter is a surprisingly simple component from a design standpoint. Because the flapping mechanism is contained fully within the gearbox frame. The frame design is a single flat plate which relies on its thickness for stiffness. The **mainframe** of the ornithopter serves the purpose of providing the mounting locations for the wing mounts, electronic components, battery, and tail assembly. The frame design is a single flat plate which relies on its thickness for stiffness.

Material selection for mainframe – Reinforced Glass Fiber plastic

Reinforced Glass Fiber plastic is a composite material formed by reinforcing plasti material with glass fibers in a matrix form. It is light weight material also can withstand sudden impact during any failure of ornithopter

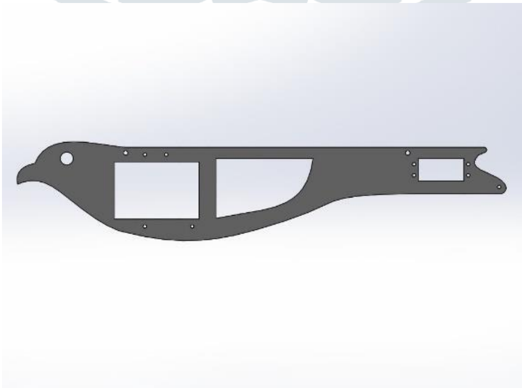


FIG. IV MAIN FRAME

F) Ornithopter Power Systems

While the electronics on the ornithopter aren't a critical system as far as the mechanical function of the machine performs, they do make up the one of the most important specifications for the project, the minimum payload capacity. Because the rest of the sizing and design of the ornithopter depends on this the weight of the computer, interface equipment, sensors, and battery must be determined first. Choosing the right motor and battery are both essential for building a successful ornithopter.

1. *Motor: Brushless outrunner motor*

   Most radio-controlled ornithopters are powered by an electric motor and battery. There are several types of electric motor that may be used in an ornithopter. The selection of motor type will depend on your specific project. The motor should be small in size. Big size motor weight a lot and weight can be very critical for the design. At the same time, the electric motor should be sturdy to provide enough torque to overcome air resistance. The brushless outrunner motors have lower KV ratings meaning they have more torque but less speed. More torque is needed than speed for this project as the motors have to turn the gears to flap. The motor also needed a front mount so that it could be mounted easily to the flapping mechanism frame instead of a separate mount just for the motor.

- Specification Motor:

  - Name - DYS D2822 2600KV Outrunner Brushless Drone Motor (Original)
  - Motor Rating - 2600 KV
  - Load Speed – 8350 rpm
  - Voltage - 7.4 V

2. *Servo motor:*

   Two servo motors are needed for positioning the tail. To position the tail servo motor should have enough torque so that the motor will hold the tail at the required position. The servo motor which rotates the tail require less torque as compared to the rudder servo.

- Specification of rudder servo motor –
  - model - TowerPro MG945 Digital High Speed Servo Motor – Standard Quality
  - Stall torque: 10kg/cm (4.8v); 12kg/cm (6v)
  - Operating voltage: 4.8 ~ 6.6v

3. *Battery:*

   Birds use their body fat to store energy for flight. In our ornithopter, the battery is the most massive component by weight and size, so it's critical to choose the right one. The battery used is a three-cell lithium polymer pack, the standard for high performance machines like airplanes on this scale because it has the best power and energy to weight ratios available.

   - Specification Of Battery –
     - Model : Orange 3300mAh 2S 25C (7.4V) Lithium Polymer Battery Pack (LiPo)
     - Model No: 3300mAh 2S 25C (7.4V)
     - Nominal Capacity: 3300 mAh
     - Minimum Capacity: 3200 mAh

4. *Motor Driver: ESC*

   We need a controller to control and regulate the speed of the brushless motor any hobby ESC is suitable the only thing to check is continuous and peak current. To reduce the weight of the ornithopter, it is better to choose the controller in the mini form.

   - Specifications of the ESC:
     - Model - Standard 30A BLDC ESC
     - Burst current (A) - 40
     - Constant current (A) - 30

5. *Communication: 433mhz rf transmitter module + receiver module*

   The Remote Controller used to transmit commands to ornithopter was a FLYSKY FS-i6s along with FLYSKY CT6B remote controller. This combination was initially chosen because it offers superior protection against interface while maintaining lower power consumption and high reliable receiver sensitivity. The controller has a fairly standard set of two joysticks, each with two degrees of freedom, two dials, and four switches.

- Specification of Controller and Receiver
  - Model - The Flysky CT6B Remote controller
  - This remote control has 6 channels and is equipped with 2.4GHz transmitter & receiver
  - This remote Control works on Radio frequency technology
  - Working distance range is 1 km

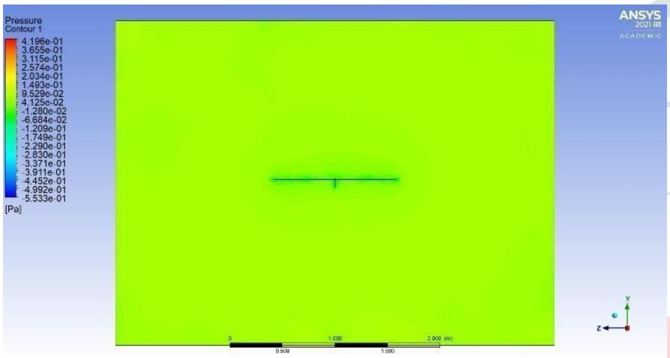
IV. ANALYSIS OF WINGS

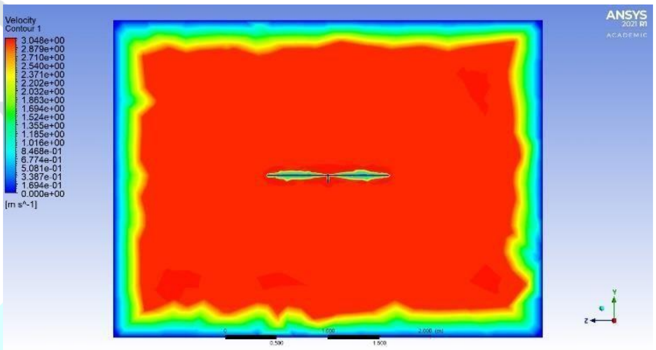
The below results show the pressure over the wing surface under the steady flow of the air over the wing area at a different angle of attack before the analysis. We will discuss the unsteady flow over the wing at different conditions. The figures allow us to understand the difference between flow velocity and pressure in different regions of the wing.

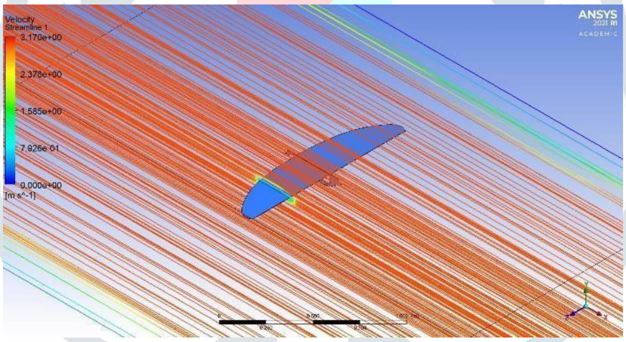
A) Flow Velocity at 3m/s

1) 0º Angle of Attack:

The pressure, velocity distribution and streamline flow over the wings surface at 0º angle of attack as shown below

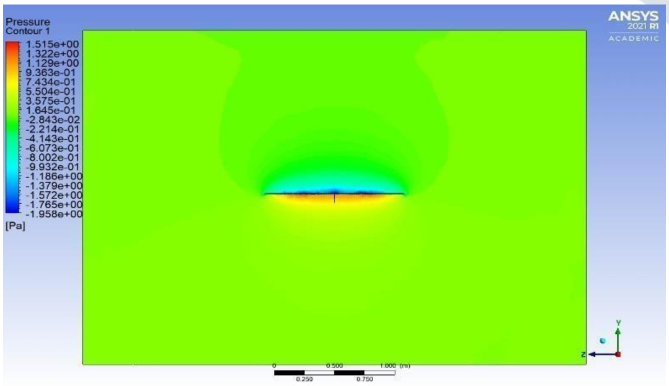


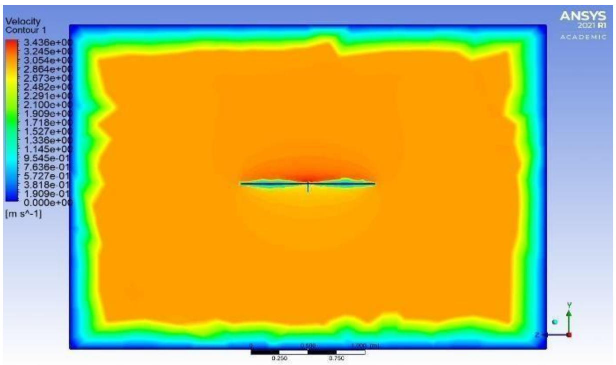


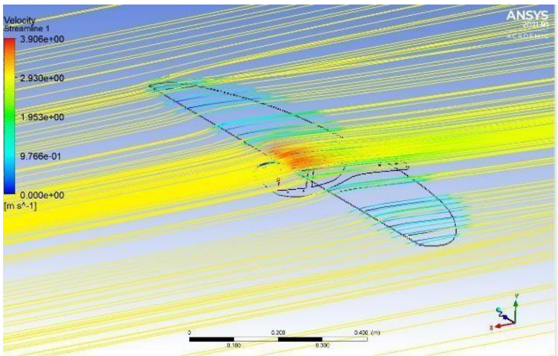


2) 5º Angle of Attack:

The pressure, velocity distribution and streamline flow over the wings surface at 5º angle of attack as shown below

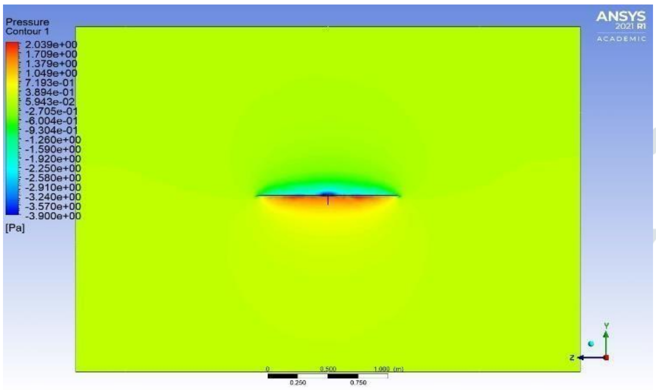


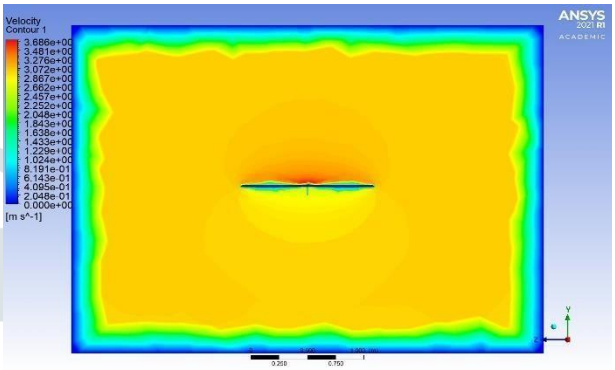


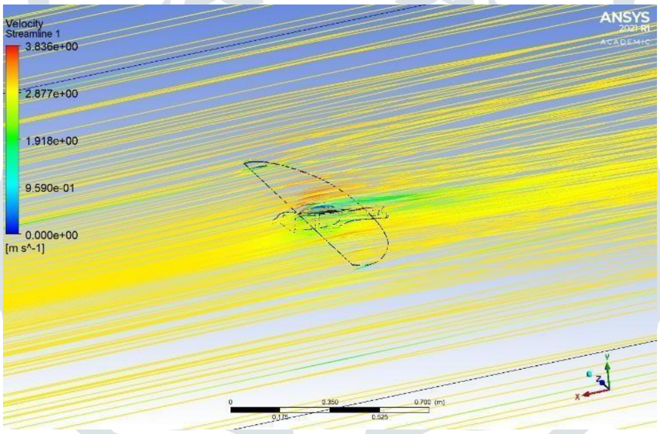


3) 8º Angle of Attack:

The pressure, velocity distribution and streamline flow over the wings surface at 8º angle of attack as shown below



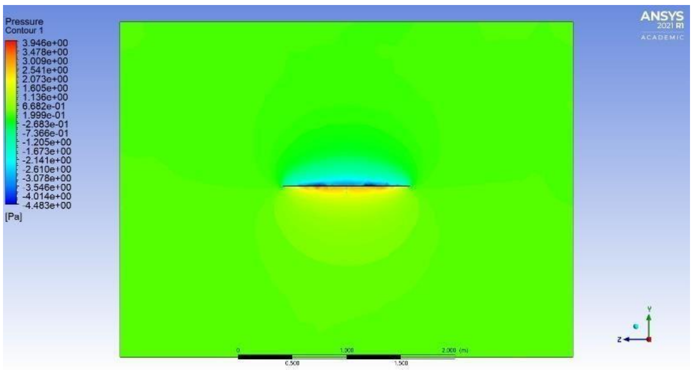


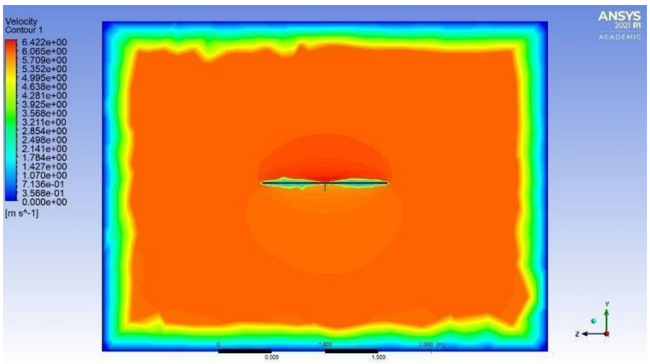


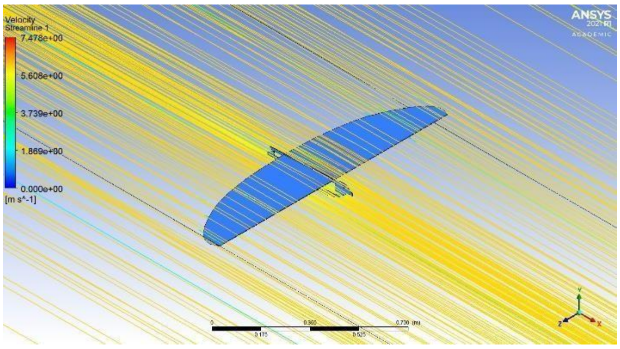
B) Flow Velocity at 3m/s

1) 0º Angle of Attack:

The pressure, velocity distribution and streamline flow over the wings surface at 0º angle of attack as shown below

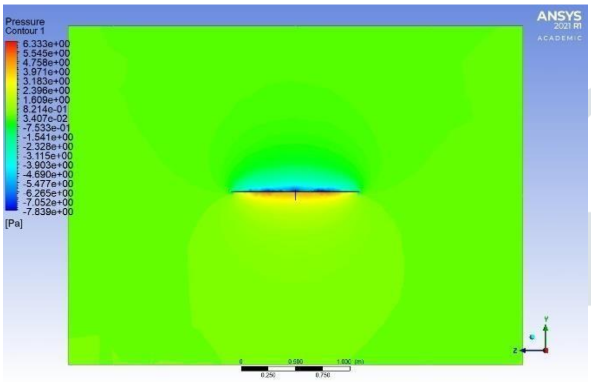


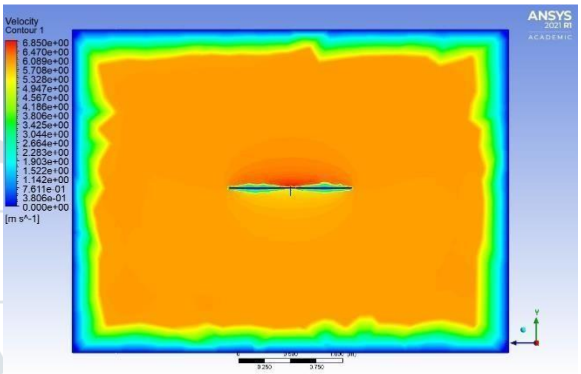


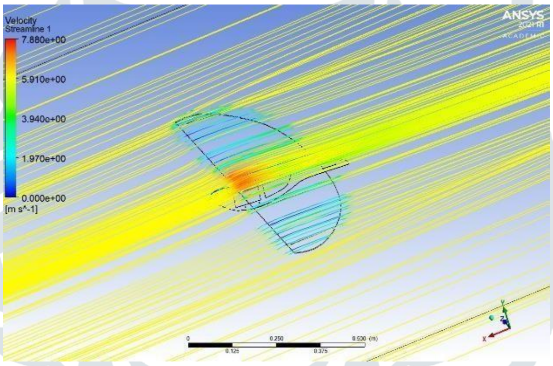


2) *5º Angle of Attack:*

The pressure, velocity distribution and streamline flow over the wings surface at 5º angle of attack as shown below

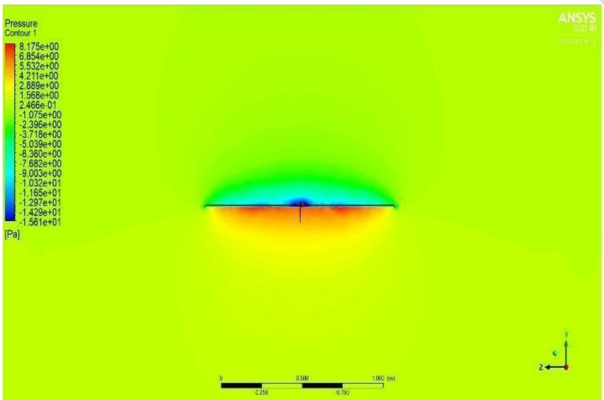


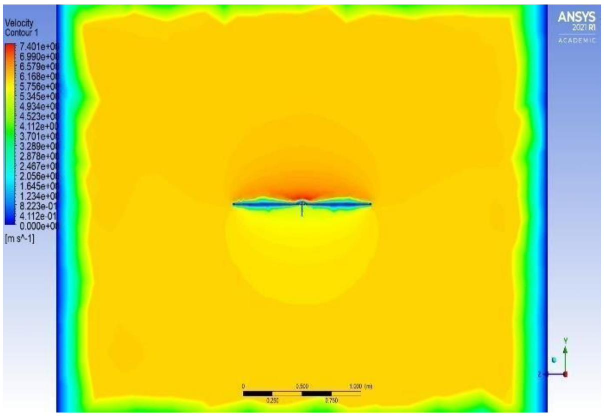


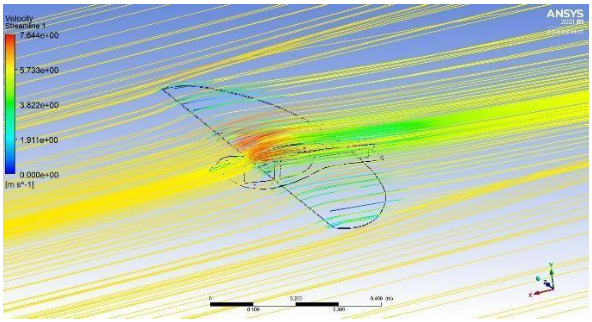


3) *8º Angle of Attack:*

The pressure, velocity distribution and streamline flow over the wings surface at 8º angle of attack as shown below







The below tables show the lift and drag forces on the wing area at a different angle of attack at a flow velocity of 3m/s & 6m/s:

Flow Velocity (m/s)	Angle of attack(deg)	Lift(N)	Drag(N)
3m/s	0deg	0.029405148	0.018329439
3m/s	5deg	0.48617451	0.058242302
3m/s	8deg	0.712547034	0.11869121
6m/s	0deg	1.1145177	0.11573685
6m/s	5deg	1.41208852	0.2188235
6m/s	8deg	2.9743457	0.46295319

Table III: Lift and Drag forces

V. CONCLUSION

The ornithopter can be designed from ground up with the needs of research in mind. All components can be designed to be as lightweight and high performance as possible to maximize payload capacity and are intended to fail in predictable and field repairable ways. In addition to this, all parts of ornithopter are simple and inexpensive to fabricate and assemble. With the newer innovations and researches in technology, we can make them as per requirements.

In this paper, various mechanical aspects that define the designing of ornithopter has studied. The study is mainly focused on a wing and gearbox design. Other things like motor, battery, ESC, servo motors, controller and receiver are just part of selection based on payload capacity and compatibility with mechanical components.

According to our project work, we calculated the lift and drag forces at three different angles of attack i.e., 0^o, 5^o and 8^o upward with flow velocity of air at 3m/s and 6m/s. The bottom side of the wings is in direct contact with the flow which results in the high-pressure region on the bottom side and low-pressure region at the top side. And this will produce a force from the higher to lower pressure region area and help the bird to fly or takeoff. But when the velocity is increased the forces also increase of both lift as well as of drag with the increase in the angle of attack. Hence as per our project works, we can conclude that as long as the angle of attack increases until the critical angle of attack reached the lift and drag forces increases and the same results will come with the flow velocity. So, in our project the maximum lift force is with 6m/s flow velocity at 8deg angle of attack and the minimum drag force is with 3m/s flow velocity at 0 degree flat position of wings.

VI. ACKNOWLEDGEMENT

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