Shreya M, 2021, 9:3
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

Design and Development of an Ornithopter by Aerodynamic and Structural Analysis

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Abstract- Ornithopter is basically an aircraft that flies by flapping its wings, unlike the conventional fixed wing aircrafts. They have wide range of applications in several fields, especially in the military. To develop an ornithopter with the desirable performance, it is important to know what type of wings should be selected. Obviously, the type of wing has to be chosen by conducting aerodynamic tests for different wings and selecting the one with the desirable characteristics. In this project, Hawk wing is chosen as the best planform based on aerodynamic analysis. The Wing was further enhanced using optimization techniques where the maximum chamber thickness had been increased from 6.8% to 8%. The maximum lift coefficient had been improved by almost 75%. Further, the structural analysis of fuselage was carried out where 0.3197mm of deformation result was obtained.

Keywords:- Ornithopter1, Flapping2, Aerodynamics3, and CFX-Ansys4.

I. INTRODUCTION

The word "ornithopter" means "bird wing". An ornithopter doesn't need to have feathers, though. Airplanes and helicopters use rotating propellers. Instead of rotation, the ornithopter imitates the reciprocating motion of a bird's wing. Designers seek to imitate the flapping-wing flight of birds, bats, and insects [1].

To develop an ornithopter with the desirable performance, it is important to know what type of wings should be selected. Obviously, the type of wing has to be chosen by conducting aerodynamic tests for different wings and selecting the one with the desirable characteristics [2].

The main aerodynamic parameters which draw our focus are the Lift and Drag coefficients for different angles of attack. Hence, we first studied the aerodynamic characteristics gathered through wind tunnel testing for some of the bird wings from the earlier researches [3].

Here, by selecting four different types of [Hawk, Shift, Quail and Starling] bird wing planforms which was designed using CATIA-V5 later there aerodynamic performance was studied by carrying out CFX-Analysis then by comparing the results the best wing was chosen for our ornithopter [4].

Then we design the same wings and validate the results computationally. From these results the best wing was selected and finally some constructive modifications had been introduced with an aim to obtain much better characteristics. Hawk wing was chosen as the best planform based on aerodynamic analysis. This will increase the pressure gradient between the upper and lower surface, subsequently resulting in the lift augmentation [5].

II. DESIGN OF ORNITHOPTER

The wing span was optimatized to 600mm and chord was finalized for 191mm.

The fuselage design should have good strength to support all components and much fulfil its deliberate purpose.

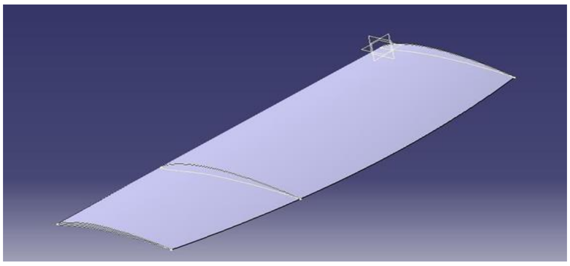

Fig 1. Hawk Wing.

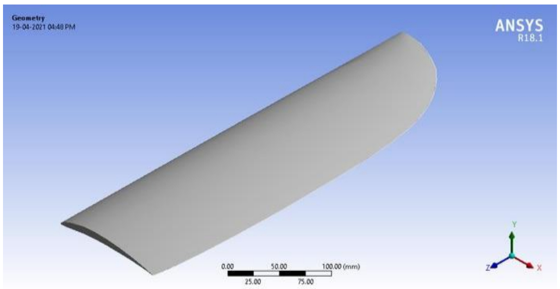

Fig 2. Optimized Hawk Wing.

Table 1. Wing Specification.

Parameters value	Value
Length	0.394m
Projected area	$0.05m^2$
Mean chord	0.132m
Thickness ratio	0.08
Aspect ratio	3.0
Root chord	0.126m
Tip chord	0.108m

So, fuselage must be designed for low rate possible without comprising on strength. Therefore, while designing it almost mandatory to fabricate it within shape of a bird. As we had selected hawk wing plan form for our ornithopter hence, the fuselage design was referred from hawk bird dimension itself.

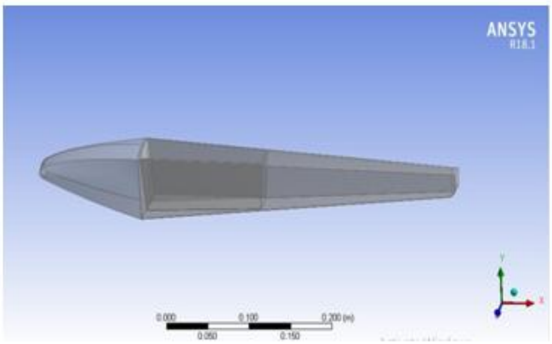

Fig 3. Fuselage.

Table 2. Fuselage Specification.

Parameters	Values
Head Section	125mm
Length	510mm
Width	85mm

III. CFX WING ANALYSIS

The numerical simulation was carried out on an aero foil wing model at static conditions where we only considered the wing section. The methodology for the simulation are as follows-

- Geometry
- Meshing
- Grid Independence Study
- Boundary Conditions
- Results

The aerodynamic performance curves comparing the Hawk wing and Optimized Hawk wing are show below. It is evident that the Optimized Hawk wing has better performance regarding the maximum lift coefficient and maximum CL/CD ratio.

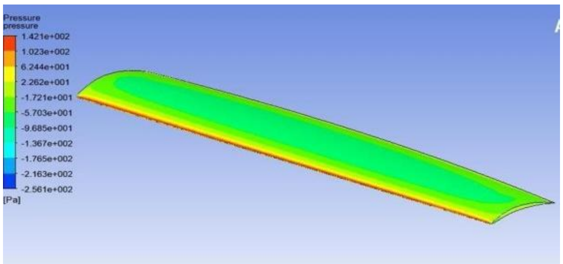

Fig 4. Pressure contour of Hawk wing.

One of the best ways to maximize lift is to increase the distance that is to be travelled by the air on the upper surface. This can be achieved by increasing the upper camber.

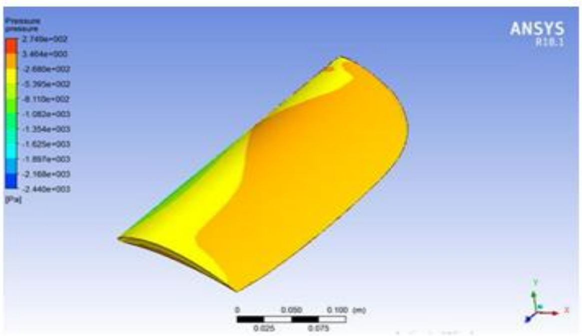

Fig 5. Pressure contour of an Optimized Hawk wing.

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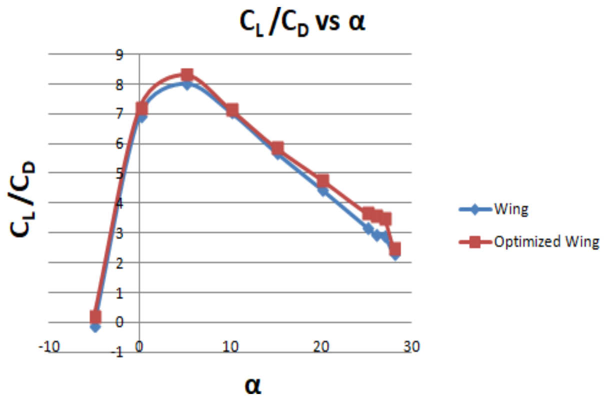

Fig 6. Chart -1: Comparison of aerodynamic performance of hawk wing and optimized hawk wing.

Table 3. Comparison of aerodynamic performance.

Hawk Bird Wing	Hawk Aerofoil Wing	Optimized Hawk Wing
Clmax =1.0 A Stall = 25°	Clmax =1.51 A Stall = 25°	Clmax =1.75 A Stall = 27°
(CL/CD)Max=3.8	(CL/CD)Max=8.03	(CL/CD)Max=8.33

IV. FLAPPING MECHANISM

Flapping mechanism is the most critical part of the ornithopter. This system is the most complex to design and fabricate because it must withstand vast forces which reverse direction several times a second while at the same time being extremely light and durable there are many kinds of flapping mechanisms [5]. The cross over shaft configuration is generally utilized for enormous ornithopters where weight could be defeat by enormous wings. Hence the shaft design used for our flapping mechanism is the transverse shaft mechanism. This mechanism works by transmitting the motor power through gear transmissions to the lifting unit. The gears were taken according to the gear ratios between the driven gear and the driving gear.

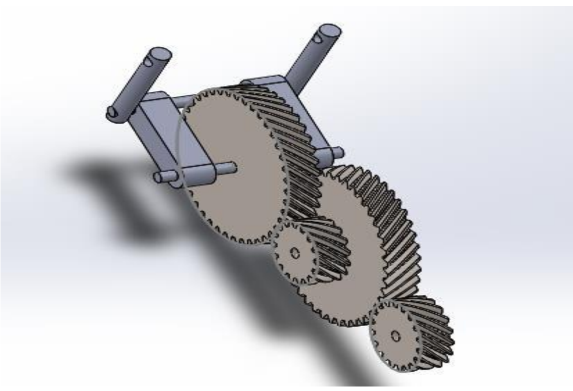

Fig 7. Flapping mechanism of the model.

The shaft design used for our flapping mechanism is the Transverse shaft mechanism. It consists of the following components.

- Gear A: m1 18t (Driving Gear connected to motor)
- Gear B: m1 41t
- Gear C: m1 16t
- Gear D: m1 41t
- Connecting rod connected to the wing

The gear labelled as Gear A, is the driving gear that is connected to the motor.
Gear B is driven by Gear A
Gear C is connected to Gear B through a shaft
Gear D is the driven gear which is connected to the wing by means of a connecting rod is responsible for moving the wings up and down. The driven gears D is connected to the wings by means of a shaft which converts the rotational motion of the driven gears into linear up and down motion for the wings.

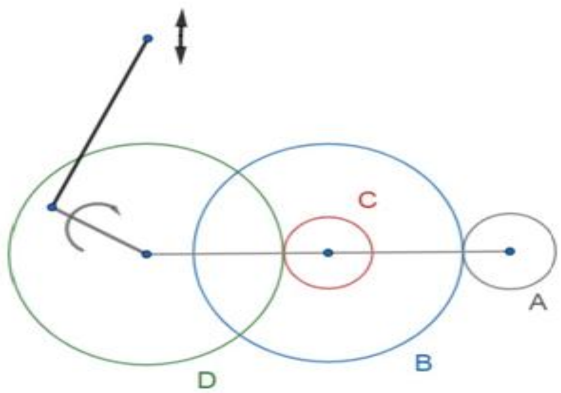

Fig 8. Transverse shaft mechanism in Linkage software.

Here, multiple gears are used to control the flapping speed. A typical motor has high angular speed. This is a very high speed for flapping and is undesirable. Therefore, the rotational speed has to be reduced.1 to 2 flaps per second. To achieve this, motor speed needs to be reduced .This can be accomplished by pairing several gears together. We can calculate the speed reduction from Gear A to Gear D using the Gear ratio.

$$\frac{n_A}{n_B} = \frac{T_B}{T_A} \quad \textbf{(1)}$$

$$\frac{n_C}{n_D} = \frac{T_D}{T_C} \quad \textbf{(2)}$$

$$\frac{n_D}{n_C} = \frac{T_C}{T_D} \qquad \textbf{(3)}$$

Dividing equation (3) by equation (1) we get:

$$\frac{n_D \times n_B}{n_C \times n_A} = \frac{T_C \times T_A}{T_D \times T_B}$$

Since gear B and gear C are connected to the same shaft, then rotational rate is equal.

$$n_B = n_C$$
$$\frac{n_D}{n_A} = \frac{T_C \times T_A}{T_D \times T_B}$$

The number of teeth's in each gear are specified as follows:

$$T_A = 18 , T_B = 41 , T_C = 16 , T_D = 41$$
$$\frac{n_D}{n_A} = \frac{16 \times 18}{41 \times 41}$$
$$n_D = 0.17 \times n_A$$

We can see that gear speed of gear D is about 5.6 times less than that of gear A [6]. The final flapping speed of wing we need is 1Hz that is, around 60rpm. This is a normal flapping rate acceptable for a bird. We need to calculate the speed of motor ηA which will give us this desired flapping speed.

If we know the value of ηD then we can calculate ηA using the above equation. ηD, the rotational speed of gear D can be calculated by carrying position analysis and velocity analysis of gear D with crank and connecting rod.

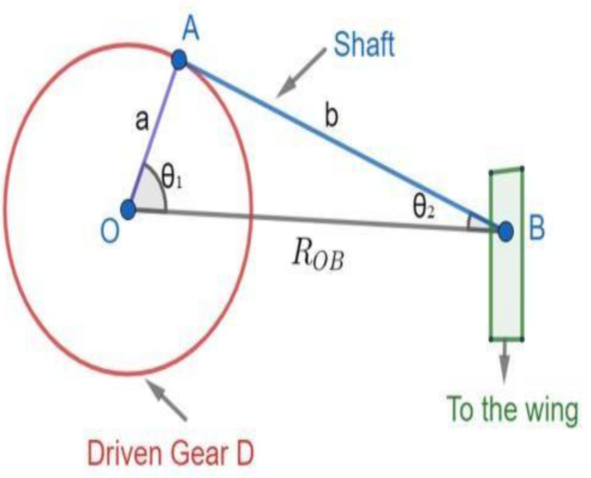

Fig 9. Shaft Mechanism.

1. Position Analysis :

Referring to Fig 8, we can write the loop closer equations as follows:

Acosθ1+ bcosθ2= R_{OB} (1)
Asinθ1- bsinθ2= 0 (2)

For a given angular position of the crank θ1, we can find the angular position of the wing θ2 and linear position R_{OB} with respect to the centre of Gear D.

2. Velocity Analysis:

If we differentiate the equations (1) and (2) w.r.t time t, we get the following equations:

-asinθ1*ω1- bsinθ2*ω2= R OB(3)
Acosθ1*ω1- bcosθ2*ω2= 0 (4)

For a given angular velocity ω1 of the crank and by knowing the angular position of the wing θ2 from the position analysis, we can determine the angular velocity of the wing ω2 as well the linear velocity R_{OB} by solving equations (3) and (4).

For example, consider the position and velocity analysis at a crank angular position θ1=30°.

For the slider crank mechanism employed in our ornithopter, the dimensions are a = 0.02m and b = 0.043m. We need to determine the position and velocity of the wing at that instant.

Using equation (2) we can write:

Sinθ2= a/b *
sinθ_1 Sinθ2=
0.02/0.043 * sin30
Sinθ2= 0.02/0.043 * sin30 = 0.2325
Θ2= sin $^{(-1)}$ (0.2325) = 13.44°

The angular position of the wing at that instant is
θ2= 13.44°

Using equation (1) we get:

Acosθ1+ bcosθ2= ROB
ROB=0.02*cos30+0.043
×cos13.44ROB= 0.059m =
59mm

The position of the wing will be at a distance of59mm from the crank.

Now let's carry out velocity analysis. The predicted value of ω_1 was 1Hz that is 60rpm.

Using equation (4) we can write:

$$\omega_2 = \omega_1 \times (a\cos\theta_1) \div (b\cos\theta_2)$$
$$\omega_2 = 60 \times (0.02 \times \cos 30) \div (0.043 \times \cos 13.44)$$
$$\omega_2 = 145\text{rpm}$$

Hence the value of η_A is 145rpm. Using the equation,

$$\eta_D = 0.17 \times \eta_A$$
$$145 = 0.17 \times \eta_A$$
$$\eta_A = 853\text{rpm}$$

Therefore, the motor speed should be controlled to around 850rpm to achieve a flapping frequency of 1Hz.

V. STRUCTURAL ANALYSIS

Structural analysis is done to an ornithopter body using ANSYS software. For structural analysis the geometry is prepared of an orthithopter body using SOLIDWORKS software and choosing the suitable materials and apply basic properties of the materials in the ANSYS. Next step is to set boundary conditions (fixed constraint, symmetry and so on) apply load on the ornithopter body.

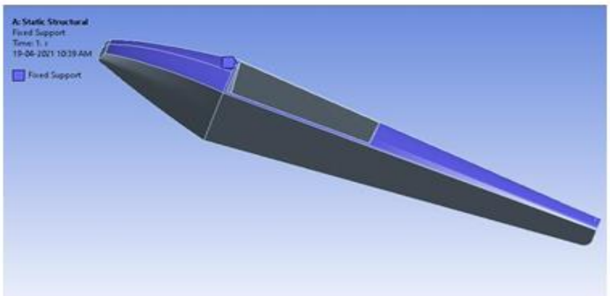

Fig 10. Fixed surface.

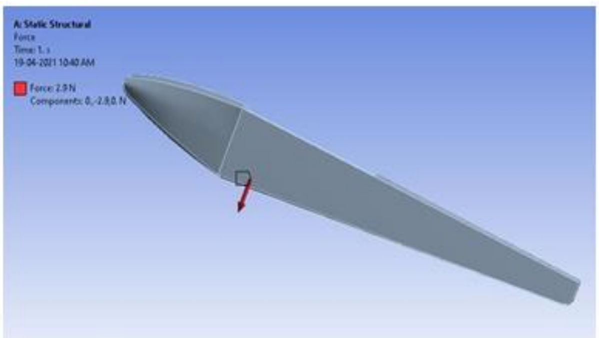

Fig 11. Force acting on the body.

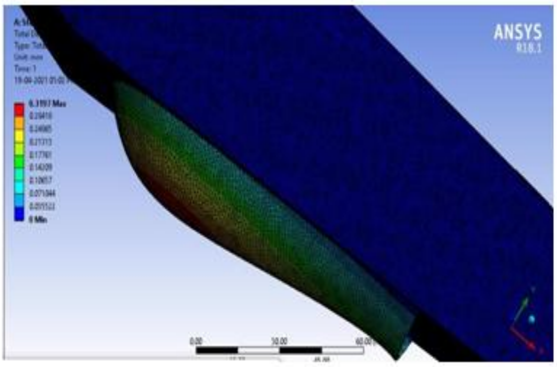

Fig 12. Total Deformation.

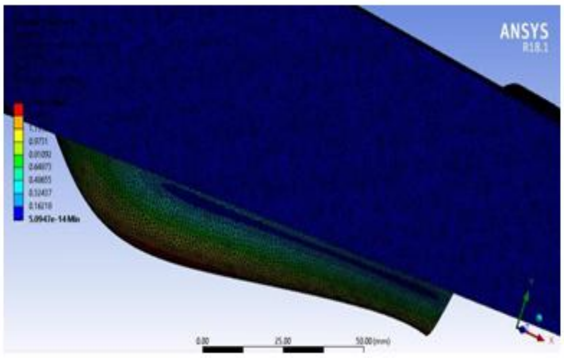

Fig 13. Equivalent Strain.

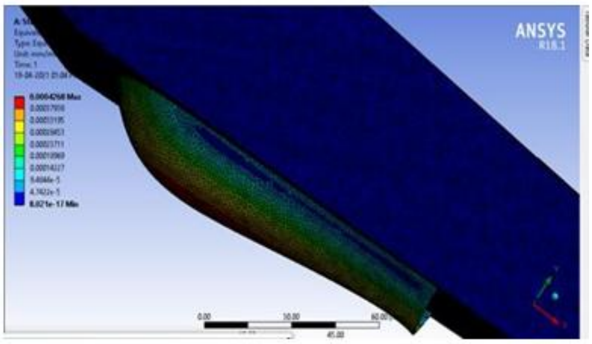

Fig 14. Equivalent Stress.

Table 4. Structural analysis results of fuselage.

Parameters	Max Value	Min Value
Deformation(Mm)	0.3197	0
Stress (Mpa)	1.4597	$5.095*10^{-14}$
Strain	$4.268*10^{-4}$	$8.021*10^{-17}$

VI. CONCLUSION

The hawk wing was selected for best bird wing planform based on the aerodynamic characteristics of maximum lift coefficient and minimum profile drag coefficient. In order to further augment the aerodynamic performance, the wing was optimized using the XFLR software.

Flow analysis carried out on the optimized hawk wing revealed that the maximum lift coefficient has been further increased. We conclude that our optimized Hawk wing has a better performance over other plan forms with respect to Quail, Swift and Starling bird wings where the maximum lift coefficient of 1.75N was obtained for optimized hawk wing. However, there was a small increase in drag as well.The structural analysis carried out for fuselage body was found 0.3197mm of deformation and 1.45MPa of stress results.

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