Analysis of Elliptical Wing Type Bird Inspired Device

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Abstract. Technology advancements have made the use of Unmanned Aerial Vehicles (UAV) in many applications. This paper aims at performing stress analysis of elliptical wing type birds using ABAQUS. The wings considered for investigation are elliptical wings of two birds having low aspect ratio. Aerodynamic forces like lift and drag are calculated and applied on proposed wing design CAD models to obtain results of stresses and structural deformation at different altitude. The material used for wing structure is carbon fiber for its various advantages over other materials. Further, shape optimization of wing structure has performed to reduce the stresses at critical regions and to reduce volume of material. This wing design analysis helps designers to build UAV in optimizing manner. In addition to above investigation, various flapping wing mechanisms 2D in SAM and 3D in ADAMS have made based on curves that are obtained by tracing the tip of wings of selected birds in TRACKER.

Keywords: Unmanned Aerial Vehicle, Elliptical Wing, Shape Optimization, Flapping Wing Mechanism.

1. Introduction

Mimicking of birds flight can be obtained by various flapping wing mechanism. Technology has been advanced towards development of UAV’s for its various applications form photography to ground inspection because of its portable nature [1]. Robust designs of flapping wings have made with the carbon fiber as light weight material for the analysis of wings at different altitudes by calculating aerodynamic forces [2]. Various optimization parameters are considered while predicting wing kinematics [3]. The dynamic analysis of wing provides useful information such as natural frequencies, damping properties and mode shapes of wings [5]. Study on flapping wing mechanism was performed for optimization of drag and lift force [4]. There is limitation to which the wing structure can sustain the maximum stresses and one of this limitation is eliminated by optimization of wing structure. The study in this paper is to determine stresses due to aerodynamic forces on wing designed structure and realizes how shape optimization analysis becomes more important as it reduces maximum stresses and also spatial displacement.

2. Mechanism of Flapping Wing

The calculation of lift and drag force is discussed in later section. The driving mechanism for flapping wing is given in the figure 2.1. The stagger angle is denoted by $\gamma$. Crank length is given by $l_1$. Linkage length is denoted by $l_2$. Rocker length is denoted by $l_3$. Angle between the crank and OO1 is denoted by $\alpha$. 

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Four bar mechanism has been developed by Freudenstein as shown in Fig. 2.2. An analytical approach has been also developed by Freudenstein. The frame is made to unity and the lengths of other links are denoted by a, b and c and the input and output angle are denoted by $\theta_2$ and $\theta_4$. Freudenstein obtained a simple scalar equation.

$$\cos(\theta_2 - \theta_4) = K_1 \cos \theta_4 - K_2 \cos \theta_2 + K_3 \tag{1}$$

$$K_1 = \frac{d}{a} \tag{2}$$

$$K_2 = \frac{d}{c} \tag{3}$$

$$K_3 = \frac{(a^2 - b^2 + c^2 + d^2)}{(2ac)} \tag{4}$$

The above equation is called Freudenstein Equation. The above equation can be applied for the kinematic synthesis of four bar mechanisms.

### 3. Curves obtained in different Software

#### 3.1. Bird Wing Tip Curves obtained in TRACKER

Elliptical wing type birds such as sparrow and pigeon videos during their flight motion were analysed in TRACKER to determine different wing tip curves as show in Fig. 3.1.
3.2. Different 2D Flapping Mechanisms and their Curves obtained in SAM

The different wing tip curves obtained in TRACKER is useful for building different 2D flapping mechanisms in SAM.
Figure 3.2. Different 2D flapping mechanisms in SAM.
3.3. Different 3D Flapping Mechanisms in ADAMS

Different 3D flapping mechanisms are made in ADAMS for simulation purposes.

![Different 3D Flapping Mechanisms in ADAMS](image)

**Figure 3.3.** Different 3D flapping mechanisms in ADAMS.

4. Selection of Wing Material

Selection of wing material is important factor from aerodynamic forces point of view. The material selected is carbon fiber which has following material properties as listed below:

- Modulus of Elasticity, $E = 135$ Gpa,
- Density, $\rho = 1600$ Kg/m$^3$,
- Ultimate compressive strength $\sigma_c = 1200$ Mpa,
- Ultimate tensile strength $\sigma_t = 1500$ Mpa,
- Shear Modulus = 5 Gpa and Poisson’s ratio = 0.3.
5. Shape of Bird Wing
The birds considered for investigation are elliptical wing type of birds. They have low aspect ratio, tight maneuvering, fast take offs and high speed for short period of time. Few examples are wood pigeon, hooded crow, raven, blackbird, pheasant, and sparrows. For analysis, two birds, wood pigeon and hooded crow are considered.

6. CAD Design of Wing Structure
Proposed design of wing structure of wood pigeon and hooded crow are shown in Figure 6 (a), (b), (c) and (d). The wing structure of wood pigeon has wing span of 0.751 m in x direction and 0.187 m in y direction. The wing structure of hooded crow has wing span of 0.925 m in x direction and 0.19 m in y direction. The weight of designed wing structure of wood pigeon is 388.76 g and weight of designed wing structure of hooded crow is 562.4 g.

Figure 6. (a). Wood Pigeon.  Figure 6. (b). Wood Pigeon wing structure design.

Figure 6. (c). Hooded Crow.  Figure 6. (d). Hooded Crow wing structure design.

6.1. Lift and Drag Calculations
Considering the flight to be 2D (motion in x and y direction), the values for drag and lift are calculated using following equations:

\[ F_{x,0} = \frac{1}{2} C_D \rho A V^2 \]  \hfill (5)
\[ F_{y,0} = \frac{1}{2} C_L \rho A V^2 \]  \hfill (6)

and

\[ V = \sqrt{V_x^2 + V_y^2} \]  \hfill (7)
Fx,0 is Drag Force, Fy,0 is Lift Force, C_D and C_L are Coefficients of Drag and Lift respectively, velocity of wind is given by V, Density of air is given by ρ, Velocity in forward direction (x direction) is given by V_x and velocity in y direction is given by V_y, wing area is given by A. The density of air changes with altitude and hence the aerodynamic forces lift and drag also changes. The variation of density with altitude is given in table 1.

### Table 1. Density variation with altitude [2].

| Sl. No. | Altitude (m) | Density (Kg/m³) |
|---------|--------------|-----------------|
| 1.      | 60           | 1.215           |
| 2.      | 500          | 1.165           |

### Table 2. Wing specifications for elliptical wing type birds [1].

| Sl. No. | Bird Name       | Category                      | Mass (kg) | Span (m) | Area (m²) | Velocity (m/s) | Wingbeat Frequency (Hz) |
|---------|-----------------|-------------------------------|-----------|----------|-----------|----------------|-------------------------|
| 1.      | Wood Pigeon     | Elliptical wing (Low Aspect Ratio) | 0.495     | 0.751    | 0.0797   | 15.4          | 5.61                    |
| 2.      | Hooded Crow     | Elliptical wing (Low Aspect Ratio) | 0.553     | 0.925    | 0.147    | 10.5          | 3.84                    |

The data for wingbeat frequencies and speeds of birds are calculated by Pennycuick [1] and are given in table 2. The calculated values of lift and drag forces are given in table 3. The values are obtained from the equations (5) and (6).

### Table 3. Calculated values of lift and drag with varying altitude.

| Sl. No. | Bird Name     | Altitude (m) | Density (kg/m³) | Drag (N) | Lift (N) |
|---------|---------------|--------------|-----------------|----------|----------|
| 1.      | Wood Pigeon   | 60           | 1.215           | 0.332    | 2.974    |
| 2.      | Wood Pigeon   | 500          | 1.165           | 0.319    | 2.851    |
| 3.      | Hooded Crow   | 60           | 1.215           | 0.285    | 2.550    |
| 4.      | Hooded Crow   | 500          | 1.165           | 0.273    | 2.445    |
7. Modelling in ABAQUS

The CAD model of wing structure is modelled in ABAQUS having material properties of carbon fibre. The procedure used for analysis is General-Dynamic Explicit. Concentrated forces on designed wing structures have been applied to obtain stresses and spatial displacements. The thickness for wing structure in both the cases of design are taken to be 4 mm. The base of the wing is fixed to the main body structure and therefore fixed boundary conditions are applied defined as ENCASTRE in which all the six degrees of freedom ($U1 = U2 = U3 = UR1 = UR2 = UR3 = 0$) have given zero value.

8. Results Without Optimization and With Shape Optimization

8.1. Without Optimization of Wing Structure

Stress and Displacement results of wood pigeon for altitude of 60 m and 500 m are as shown in Fig. 8.1. (a), (b), (c) and (d).

![Figure 8.1. (a) Stress at altitude of 60 m](image1)
![Figure 8.1. (b) Spatial displacement at altitude of 60 m](image2)

![Figure 8.1. (c) Stress at altitude of 500 m](image3)
![Figure 8.1. (d) Spatial displacement at altitude of 500 m](image4)

Stress and displacement results of hooded crow for altitude of 60 m and 500 m are as shown in Figure 8.1. (e), (f), (g) and (h).
Figure 8.1 (e) Stress at altitude of 60 m

Figure 8.1 (f). Spatial displacement at altitude of 60 m

Figure 8.1 (g). Stress at altitude of 500 m

Figure 8.1 (h). Spatial displacement at altitude of 500 m

Table 4. Maximum stress and displacements at varying altitudes

| Sl. No. | Bird Name      | Altitude (m) | Maximum Wing Stress (KPa) | Maximum Spatial Displacement (m) |
|---------|----------------|--------------|----------------------------|----------------------------------|
| 1.      | Wood Pigeon    | 60           | 2236                       | 0.00072                          |
| 2.      | Wood Pigeon    | 500          | 2144                       | 0.00069                          |
| 3.      | Hooded Crow    | 60           | 17.66                      | 0.0041                           |
| 4.      | Hooded Crow    | 500          | 17.910                     | 0.0043                           |

8.2. With Shape Optimization for Wing Structure of Wood Pigeon at Altitude of 500 m

To reduce the maximum stress at critical regions and spatial displacements, shape optimization of wing structure in ABAQUS has performed.
8.3. Comparison between Stresses and Displacements of Wing Structure Design With and Without Shape Optimization of Wood Pigeon Wing Structure at an Altitude of 500 m

Below table shows clearly how shape optimization can help designers to reduce maximum stress and spatial displacement in order to mimic the flight as accurately as possible.

| Sl. No. | Analysis Type          | Altitude (m) | Maximum Wing Stress (KPa) | Maximum Spatial Displacement (m) |
|---------|------------------------|--------------|---------------------------|----------------------------------|
| 1.      | With Optimization      | 500          | 1391                      | 0.00019                          |
| 2.      | Without Optimization   | 500          | 2144                      | 0.00069                          |

Below figure shows the comparison between stresses of wing structure design with shape optimization and without optimization.

![Figure 8.3. (a). Stress at altitude of 500 m with shape optimization](image1)

![Figure 8.2. (a). Stress at altitude of 500 m without optimization](image2)

9. Conclusions

In this paper, two birds having elliptical wings of low aspect ratio are considered for calculation of aerodynamic forces and its effect on proposed design of wing structure is examined with variation in altitude. It is observed from the stress results that, compared to wood pigeon wing structure design, the stresses are less on hooded crow wing structure design. It is worth to be noted that with the help of shape optimization the maximum stresses are further reduced to 35% of initial maximum stress in the case of wood pigeon wing structure at an altitude of 500 m. Hence, shape optimization analysis proves to be effective method to reduce maximum stresses.

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