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Airflow Modelling Over a Flying Bird

Nur Allyia Noor Hizan[1,*], Nurul Irshadiah Mohd Fardil[2], Priya Tharshini Ayasamy[3]

[1] Department of Mechanical Engineering, Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia

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ABSTRACT

This research investigates the aerodynamic properties of a bird in flight by simulating airflow around its body using ANSYS Fluent. The primary objectives are to analyse how variations in flight speed affect pressure distribution, and drag coefficient. Utilizing computational fluid dynamics (CFD) methodology, the study model's airflow to provide a comprehensive analysis of both internal and external flow dynamics. A geometric model of the bird is developed, and a fluid domain is established around it. A grid independence test ensures the accuracy of the results, which are not significantly influenced by mesh size. Various boundary conditions are applied to replicate real flight scenarios, including fixed wall conditions on the bird's surface and specific inlet velocity profiles. The findings reveal that increased airflow velocity significantly impacts drag coefficient and drag force. The pressure distribution around the bird's body is examined to identify high and low-pressure areas, crucial for understanding aerodynamic efficiency. This research enhances the understanding of avian flight mechanics and offers insights that could improve the design of bio-inspired aerial devices.

1. Introduction

Birds have specific body structures and wing forms that reduce drag to adapt to flight. The trade-off between lift and drag has been thoroughly studied, with a focus on low Reynolds numbers as a defining feature of avian flight [1,2]. Aerodynamic methods like weight support at modest speeds or high-performance migratory flight are associated with morphological changes between species [3,4]. The distribution of pressure is essential for effective flying and fits in nicely with accepted aerodynamic theories [1]. CFD clarifies the aerodynamic behavior of biological forms by enabling detailed simulations of airflow around them. CFD has been used in studies to examine damage scenarios and self-propelled bird models, showing how these effects drag and lift coefficients [5,6]. There has been much research done on the relationship between different airflow velocities and flight performance. As seen in species-specific adaptations, birds can reduce drag and increase lift by

* *Corresponding author.*
E-mail address: cd210060@student.uthm.edu.my

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modifying their wingbeat kinematics and wake flow dynamics [3,7]. These variations are essential for energy-efficient flight across different environmental conditions.

Pressure distribution directly influences drag. Simulations have detailed how flow patterns evolve around bird wings and bodies, aligning with theoretical aerodynamic models [8,6]. Gliding raptors' CFD studies highlight how useful pressure-based techniques are for evaluating flight performance [9]. Aerodynamic efficiency is mostly determined by drag force and coefficients. Research on gliding and flapping motion shows how morphological and behavioral adaptations optimize these factors [10,4]. Owls and barn swallows are two examples of creatures that effectively reduce drag [8]. Grid independence ensures CFD reliability. Structured and mosaic meshes have been shown to improve simulation accuracy for complex aerodynamic phenomena [11,6]. Validation through wind tunnel experiments further strengthens their application in avian studies [12].

The objective of this study is to analyze how varying airflow velocities affect the pressure distribution, drag coefficient, and drag force around a bird's body using computational fluid dynamics (CFD) simulations. By simulating different flight conditions, the study aims to understand the aerodynamic forces acting on the bird, specifically how velocity changes influence the pressure on the bird’s surface and the drag experienced during flight. This analysis provides valuable insights into the bird's flight performance and helps optimize bio-inspired flight designs.

2. Methodology

2.1 Geometry of the Wing Birds and Box

In order to capture flow phenomena without interference from boundaries, the computational domain is modelled as a rectangular box with dimensions of 5 m × 5 m × 5 m. The bird is positioned in the middle of the box and measures 0.367 m × 0.05 m × 0.19 m. Accurate wake capture and symmetrical flow development are therefore guaranteed as shown in Figure 1.

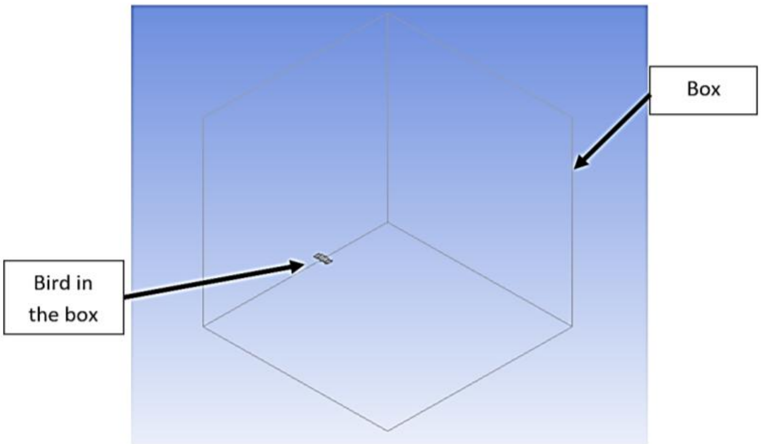


Fig. 1. The geometry of model

2.2 Governing Equation

The continuity and momentum equations are part of the Reynolds-Averaged Navier-Stokes (RANS) equations, which are used to model the airflow. The flow is taken to be level, three-dimensional, and fully developed for the purposes of this research. According to Newtonian theory, the fluid is incompressible. The turbulence model and the energy equation are also part of the analysis [13-15].

Continuity equation:

$$\nabla \cdot v = 0 \tag{1}$$

Momentum conservation:

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot\ (\rho v \cdot v) = -\nabla p + \nabla \cdot (\mu \nabla v) + f \tag{2}$$

Turbulence kinetic energy (turbulence model):

$$\frac{\partial k}{\partial t} + v \cdot \nabla k = \nabla \cdot \left[\left(v + \frac{v_t}{\sigma_k}\right) \nabla k\right] + P_k - \epsilon \tag{3}$$

Turbulence dissipation rate (turbulence model):

$$\frac{\partial \epsilon}{\partial t} + v \cdot \nabla \epsilon = \nabla \cdot \left[\left(v + \frac{v_t}{\sigma_\epsilon}\right) \nabla \epsilon\right] + C_1 \frac{\epsilon}{k} P_k - C_2 \epsilon^2 \tag{4}$$

2.3 Meshing of the Flying Birds

The mesh technique is configured to generate automatically (Figure 2). The closeness and curvature made it possible to successfully improve important areas like edges and curves. The grid independent test (GIT) stage will be used to adjust or revise the element size until there is no apparent change in the intended characteristics. The smaller mesh details were created for the area around the bird's wings, and the initial element size produced was 0.1 m.

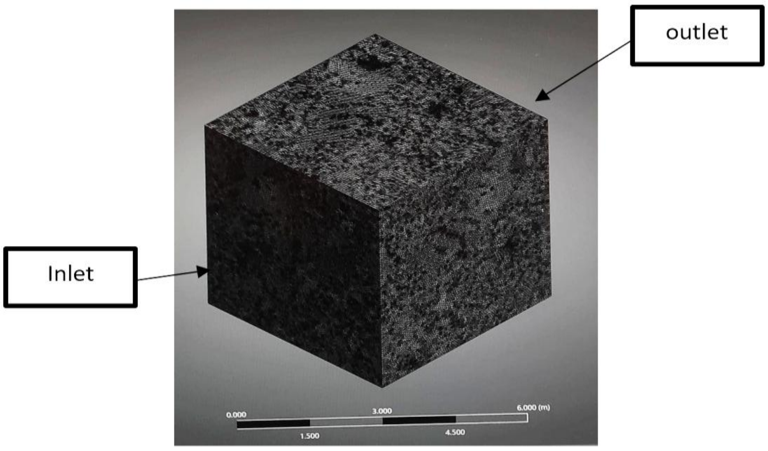


Fig. 2. Meshing model of the box

2.4 Parameter Assumptions and Boundary Conditions

The air is treated as an incompressible, Newtonian fluid since the flow speeds are low. A no-slip condition is applied to the bird's surface to capture aerodynamic effects, while the box walls are treated as slip boundaries. The flow is steady and three-dimensional, with velocities set at 10 m/s, 12 m/s, 14 m/s, and 16 m/s to represent typical flight conditions [12]. The k-epsilon Realizable turbulence model is used to study airflow patterns, wakes, and separation around the bird. The following Table 1 lists the density and viscosity of the material.

Table 1
Materials properties

Material	Air
Density (kg.m-3)	1.225
Viscosity (kg.m-1. s-1)	0.000017894

2.5 Analysis

We use velocity calculations in this study to examine the airflow close to the bird's wing. Velocity is calculated using the continuity equation and shows the flow patterns [6]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{5}$$

To understand lift, we look at how pressure changes throughout the bird's body. The Bernoulli equation is used to calculate this:

$$P+\frac{1}{2}\rho v^2=\text{constant} \tag{6}$$

To determine how aerodynamic the bird is, we also compute the drag coefficient (C_d) using [16]:

$$C_d=\frac{2F_d}{\rho v^2 A} \tag{7}$$

Here, v represents velocity, A is the reference area, and F_d is drag force. Lastly, the drag force is calculated using [17]:

$$F_d=\frac{1}{2}\rho v^2 C_d A \tag{8}$$

2.6 Grid Independence Test

In this study, a grid independence test was conducted to ensure that the Computational Fluid Dynamics (CFD) simulations of airflow over a flying bird yield accurate and reliable results, independent of the computational grid resolution. This process involved creating a series of computational grids with varying resolutions, ranging from coarse to fine meshes. CFD simulations were performed on each mesh to analyse the airflow characteristics around the bird. Key aerodynamic parameters, specifically drag force and drag coefficient, were calculated and compared across different mesh resolutions [18].

3. Results
3.1 Grid Independence Test

The results were analysed to determine the point at which further refinement of the mesh did not lead to significant changes in these parameters, indicating grid independence [18]. This approach aligns with established practices in CFD to ensure the accuracy and reliability of simulation results. The drag coefficient calculated using the general formula while the drag force was the assume numbers The drag coefficient of 0.016 and the drag force of 2.6 N indicate that the chosen element size of 0.1 m was sufficiently refined to provide reliable results in terms of aerodynamic behaviour.

The test number, element size, element number, drag coefficient and drag force are displayed in Table 2 and Figure 3.

Table 2
The number of grid independence test

GIT	Element size (m)	Amount of element	Drag coefficient	Drag force (N)
1	0.3	44580	0.016	2.5
2	0.1	221411	0.0172	2.6
3	0.05	1491932	0.0178	2.7

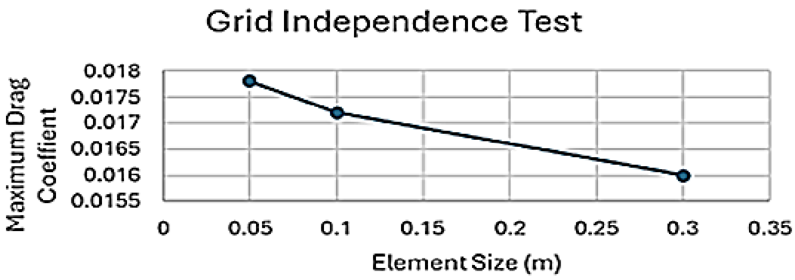
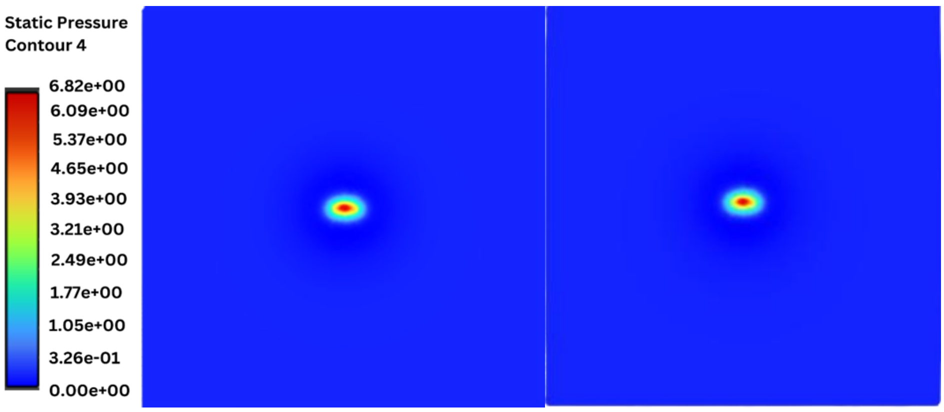


Fig. 3. Grid independence test

3.2 Static Pressure Distribution on Flying Birds with Varying Velocity

Figure 4 show the static pressure distribution at four different velocities: 10 m/s, 12 m/s, 14 m/s, and 16 m/s. As the velocity increases, the pressure distribution changes, impacting the bird's stability and energy efficiency. At 10 m/s, the static pressure distribution provides a baseline for comparison. At 12 m/s, there is a noticeable change, indicating how increased speed affects aerodynamic forces. At 14 m/s, further changes are observed, showing a trend as velocity rises. At 16 m/s, the highest velocity studied, the pressure distribution is significantly different, highlighting the impact of high-speed flight on aerodynamics [1].



(a) (b)

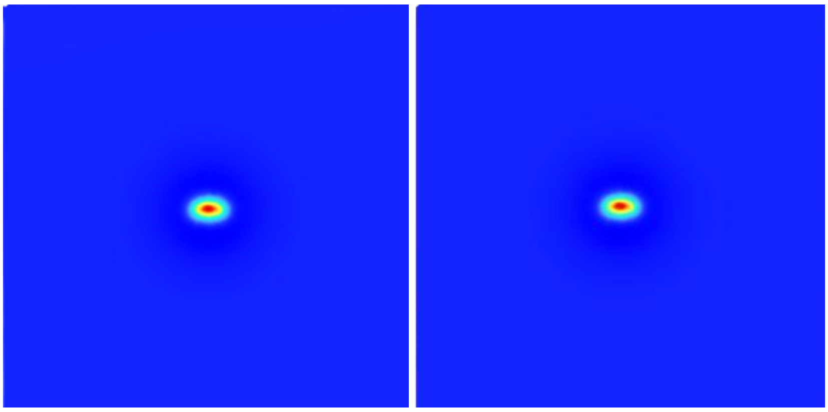


Fig. 4. Static pressure distribution in (a) v = 10 m/s, (b) v = 12 m/s, (c) v = 14 m/s, (d) v = 16 m/s

3.3 Drag Coefficient and Drag Force

Table 3 presents the drag coefficient and drag force at the same velocities. The drag coefficient, a dimensionless number representing drag per unit area, and the drag force, the actual force exerted by air resistance, both increase with velocity. At 10 m/s, the drag coefficient is 0.450, and the drag force is 11.5 N. At 12 m/s, the drag coefficient increases to 0.470, and the drag force rises to 16.0 N. At 14 m/s, the drag coefficient is 0.500, with a drag force of 21.0 N. At 16 m/s, the highest drag coefficient of 0.550 is recorded, with a drag force of 28.0 N. These results indicate that higher speeds result in greater air resistance, which the birds must overcome during flight. Figure 5 and Figure 6 shown the graph of the maximum drag coefficient and drag force in different velocity.

Table 3
Drag coefficient and drag force over varying velocities

Bird	Velocity (m/s)	Drag coefficient	Drag force (N)
1	10	0.450	11.5
2	12	0.470	16.0
3	14	0.500	21.0
4	16	0.550	28.0

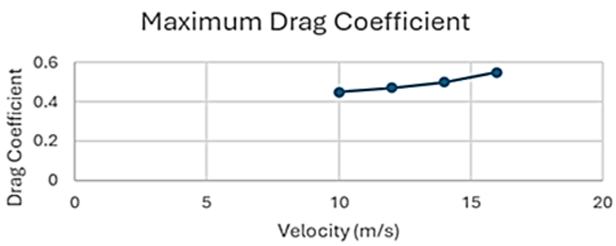


Fig. 5. Maximum drag coefficient

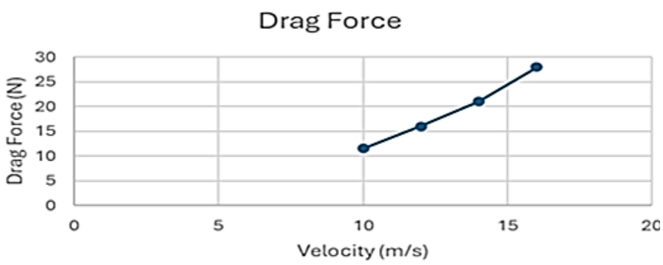


Fig. 6. Maximum drag force

4. Conclusions

In conclusion up, this study has effectively uncovered important facts on birds' aerodynamic performance, especially the effect of different airflow velocities on drags. The findings show that the drag coefficient and drag force both dramatically increase with velocity, highlighting the difficulties birds have while flying at higher speeds. The intricacy of the observed flow topology, however, indicates that further research is required to confirm these results and expand our knowledge of avian aerodynamics. To completely understand the complex relationships between airflow and avian shape and to further our understanding of this topic, more research will be necessary.

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