

Aerodynamic Evaluation of Wing-in-Ground Effect Craft Designed Using a Biomimetic Approach

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Abstract

Biomimicry provides a design framework that emulates biological characteristics to exploit their functional advantages. This study presents a biomimetic-based aerodynamic assessment of wing-in-ground (WiG) configurations inspired by flying animals, including birds and mammals, using computational fluid dynamics (CFD). Three biomimetic wing models were developed by translating biological characteristics—such as body size, wing geometry, and flight behavior—into engineering design parameters relevant to near-surface flight. Numerical simulations were performed to evaluate lift, drag, lift-to-drag ratio, and trim stability under various operating conditions. The results demonstrate that each biomimetic configuration exhibits distinct aerodynamic performance consistent with its biological inspiration. The brown pelican-inspired model achieved the highest lift force, reaching approximately 68 kN, reflecting its natural adaptation for efficient lift generation near the surface. In contrast, the sugar glider-inspired model produced the lowest lift, approximately 37 kN, corresponding to its lightweight gliding characteristics. Overall, the findings confirm that biomimicry provides a rational and effective framework for preliminary WiG craft design, enabling aerodynamic performance to be systematically tailored through biologically inspired geometrical adaptations.

Keywords Biomimicry; Wing-in-Ground (WiG) effect; Aerodynamic analysis; Brown pelican; Sugar glider

1 Introduction

Biomimicry is an interdisciplinary design approach that seeks to emulate functional principles observed in biological systems to address complex engineering challenges. In fluid dynamics, numerous biological organisms—such as birds, fish, and marine mammals—have evolved highly efficient mechanisms for lift generation, drag reduction, and stability in air-water interaction environments. These natural adaptations have inspired engineering innovations aimed at improving aerodynamic and hydrodynamic performance across a wide range of transportation systems

(Yun et al., 2010).

Wing-in-Ground (WiG) effect craft represent a unique class of vehicles that operate in close proximity to a surface, typically water, to exploit the ground effect phenomenon. This effect results in increased lift and reduced induced drag due to the interaction between the wing and the underlying surface, offering significant advantages in terms of fuel efficiency and cruising speed compared to conventional marine or airborne vehicles. WiG craft, also known as ground-effect or surface-effect vehicles, have been extensively studied from both theoretical and practical perspectives. Foundational works by Rozhdestvensky (2006) and Matveev (2003) established the fundamental aerodynamic principles governing ground effect, emphasizing the critical roles of wing geometry, angle of attack, and ground clearance in determining vehicle performance and stability.

The ground effect phenomenon itself has long been recognized in aviation and automotive engineering, where aircraft during take-off and landing, as well as high-performance racing cars, experience enhanced lift-to-drag ratios when operating near a surface. This increase in aerodynamic efficiency has motivated sustained research efforts to harness ground effect as a primary operating principle for vehicle design. In the context of WiG craft, optimizing lift-to-drag characteristics is essential for achieving stable

Article Highlights

- Biomimetic approach applied to wing-in-ground (WiG) aerodynamic design.
- CFD used to evaluate lift, drag, and stability of bio-inspired models.
- Biomimicry enables systematic performance tuning for preliminary WiG design.

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trim conditions, reduced resistance, and safe take-off behavior.

Advancements in computational fluid dynamics (CFD) have significantly expanded the capability to analyze and optimize WiG craft designs. CFD-based studies allow detailed investigation of flow structures, pressure distributions, and force interactions that are difficult to capture experimentally. Previous research by Xie et al. (2015) and Kim et al. (2018) demonstrated the reliability of CFD simulations in predicting aerodynamic and hydrodynamic performance parameters of WiG vehicles, including resistance, lift characteristics, and trim stability. Such numerical approaches have become an essential component in modern WiG design methodologies.

Parallel developments in marine hydrodynamics have shown that the application of lift-generating devices, such as hydrofoils, stern foils, and ducted vanes, can substantially improve vessel performance by reducing resistance and enhancing dynamic stability. Studies on high-speed patrol vessels have reported measurable improvements in lift-to-drag ratios and resistance reduction through the application of stern foils and hydrofoil systems (Syahrudin et al., 2020; Budiyo et al., 2021; Budiyo et al., 2021). These findings underline the importance of lift augmentation and flow control strategies in high-speed marine vehicles, providing a strong conceptual foundation for extending similar principles to WiG craft operating in the air-water interface.

Biomimetic design approaches have further enriched this research domain. Investigations by Fish et al. (2011) and Triantafyllou and Triantafyllou. (2016) demonstrated that bio-inspired geometries and kinematic principles can yield superior performance in terms of efficiency, maneuverability, and stability under varying environmental conditions. Despite these advances, the integration of biomimetic

principles into WiG craft design remains relatively limited, particularly in systematic evaluations that combine biomimetic geometry development with validated hydrodynamic and aerodynamic analyses.

Therefore, this study aims to address this gap by conducting a hydrodynamic and aerodynamic evaluation of a biomimetic-based Wing-in-Ground effect craft. The WiG models are developed by adopting geometric characteristics inspired by selected biological forms with varying aspect ratios. Using CFD simulations validated against existing experimental data, this research investigates trim stability, resistance components, and take-off performance under planning conditions. The results are expected to provide new insights into the potential of biomimetic design strategies to enhance the performance and operational stability of future WiG craft. The novelty of this work is the introduction of a comparative, biology-driven WiG design framework that links biomimetic wing geometry with ground-effect flow behavior and providing new insights beyond conventional WiG configurations and existing biomimetic studies.

2 Research methods

The final goal of this paper is to create a feasible prototype with performance according to previously determined needs after knowing which biomimetic model best suits those needs. Therefore, this paper wants to see the characteristics such as lift and resistance of the prepared models. Figure 1 shows the research flow carried out in this study.

2.1 Conceptual design stages

In order to fulfill its usefulness as a fast and limited

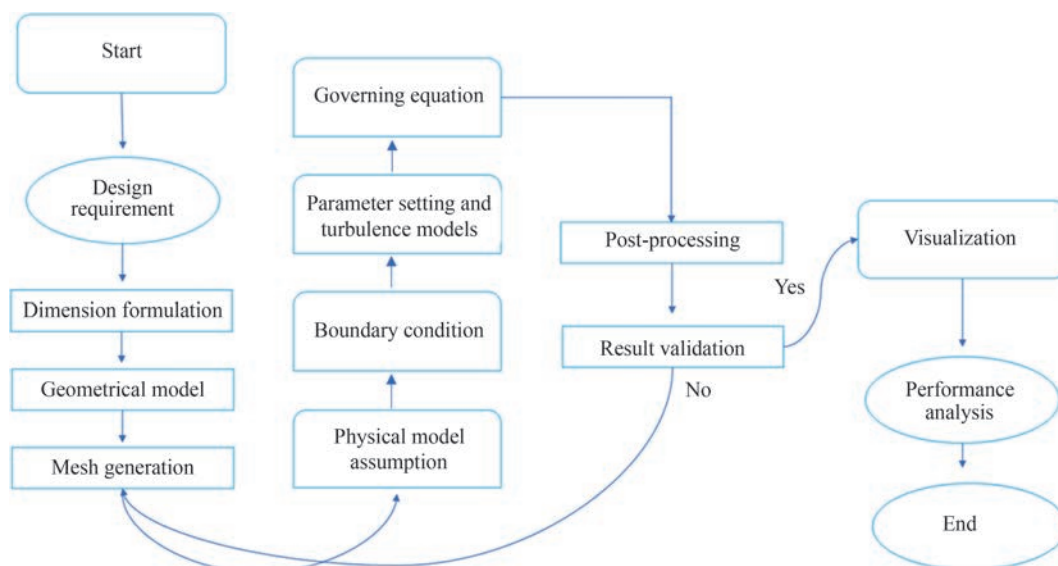


Figure 1 Overview of the research methodology

means of transportation. The design requirements comply with applicability from two commercial WIGs data and comparisons to start the design process. The size of these two types of WIGs is not the main determinant of the model that will be used for further research but to see the capacity and capabilities of current commercial WIGs.

From the data above, it can be concluded that the general passenger capacity that can be accommodated by a commercial WIG is 8–10 people with a maximum distance of 650 km. The existing dimensions are also not much different and variations are in the shape of the wings. This data will be the limitation of the next design process so that the WIG design is not too far from the existing specifications. Considering the distance measured is 55.39 km a WIG with a distance of about 650 km can travel around the island group many times. The infrastructure that is usually built to support small boats can be used as a parking lot. By following the existing commercial specifications, the design requirements determined. It should also be noted that the wave height is in the range of sea state 1 to sea state 3 so that it is safe enough to be passed by WIG except in stormy and rainy conditions. The spectrum of sea conditions can be seen through the Pierson-Moskowitz Sea Spectrum Table.

2.2 Initial design stages

The basic model used in this study is a generic reference Wing-in-Ground (WiG) craft configuration, developed based on typical geometrical and performance characteristics reported in previous experimental investigations of WiG models in hydrodynamics towing-tank and wind-tunnel laboratories. This model is not a direct copy of any single experimental model, and therefore only qualitative consistency—rather than one-to-one quantitative matching—can be established between our CFD results and the experimental data available in the literature. This reference WiG model serves as the baseline for comparing air resistance, water resistance, lift, and pressure distributions with those of the biomimetic-modified designs. The baseline geometry is subsequently modified by adjusting the wing aspect ratio and dihedral angle according to the characteristics of each selected biological model.

The reference WiG craft adopts a complete aircraft-like configuration while following a design concept similar to the Lippisch configuration. This configuration is characterized by a relatively low aspect ratio, resulting in shorter wings with a comparatively large wing area. The main components of the reference WiG craft include:

- **Wing:** A reverse delta wing mounted on the upper fuselage (upper-wing configuration), typically employing airfoil profiles with high lift-to-drag (L/D) ratios.
- **Fuselage:** A hull section with a flat planning bottom, which may take the form of a stepped planning hull, a non-stepped hull, or a chined hull configuration.

- **Pontoons (Side Buoys):** Functioning as endplates or buoyancy elements to enhance lateral stability during take-off and landing operations.

- **Nacelle:** A propulsion system consisting of a single propeller unit.

- **Vertical Tail Plane:** A control surface responsible for directional (yaw) stability.

- **Horizontal Tail Plane:** A control surface responsible for longitudinal (heave and pitch) stability.

The principal technical specifications of the reference WiG craft are summarized in Table 1.

Table 1 Technical specification of reference WiG model

Geometry	Wing	Tail horizontal	Tail vertical
Area (m ²)	64.00	16.07	9.90
Taper ratio	0.2	1.00	0.56
Dihedral angle (°)	−14.6	0	53.00
MAC (m)	6.35	1.64	1.62
Wing span (m)	11.32	9.80	3.13
Chord root (m)	7.44	1.64	2.00
Chord tip (m)	1.49	1.64	2.00
Airfoil	CLARK Y	NACA 0012	NACA 0012
Hull form			
Length (m)	13.28		
Beam (m)	1.90		

2.3 Biomimetic modeling

Three biomimetic reference models are adopted in this study, namely the Brown Pelican (*Pelecanus occidentalis*), Flying Fish (*Cypselurus hiraii*), and Sugar Glider (*Petaurus breviceps*), selected due to their demonstrated adaptations for efficient gliding and near-surface flight, as reported in previous aerodynamic and biological studies (Rayner, 1986; Fish and Hui, 1991; Davenport, 1994; Jackson, 2000; Fish, 2011; Bishop, 2006). The brown pelican is a coastal seabird native to the coastal regions of the Americas and is well known for its large expandable throat pouch used for catching fish. As a marine carnivorous bird, pelicans frequently employ low-altitude flight close to the water surface to search for prey, a behavior that inherently exploits the ground effect phenomenon. Experimental and observational studies have shown that brown pelicans significantly reduce aerodynamic drag during near-surface gliding, with reported reductions of up to 49% due to ground effect utilization (Fish and Hui, 1991; Fish, 2011). During maneuvering, pelicans dynamically adjust their wing span by partially folding the wings for rapid turns or fully extending them into a curved configuration to achieve stable, low-speed gliding above the water surface. Adult

brown pelicans typically have an average body length of approximately 1.2 m, a wingspan of about 2.0–2.3 m, and a body mass of up to 3 kg. Observations indicate that pelicans glide at speeds ranging from 9 to 15 m/s during near-surface flight (Pennycuik, 2008; Fish, 2011).

Flying fish exhibit a unique dual-mode locomotion, combining efficient swimming with controlled gliding above the water surface. This gliding capability is primarily an adaptive response to predator avoidance (Rayner, 1986). Numerous aerodynamic studies have been conducted on flying fish due to their favorable lift-generating morphology. Flying fish are capable of gliding distances of up to 400 m with flight durations approaching 30 s and flight speeds ranging from 10 to 20 m/s (Fish, 1990; Davenport, 1994). Morphologically, the pectoral fins are enlarged and modified to function as primary lifting surfaces, while the pelvic fins act as auxiliary wings in some species. Additionally, several *Cypselurus* species exhibit a relatively flat ventral body surface, which contributes to additional lift generation during gliding. Among the various species, *Cypselurus hiraii* was selected in this study due to the availability of multiple body-shape datasets and extensive prior aerodynamic investigations. The pectoral fins serve as the primary wings, whereas the pelvic fins act as secondary wings, with the pectoral fins being significantly larger in span and area than the pelvic fins.

Sugar gliders are small arboreal marsupials capable of gliding using a patagium membrane that extends between the forelimbs and hindlimbs. Unlike engineered aircraft, sugar gliders typically exhibit glide ratios close to unity, meaning that the horizontal distance traveled is approximately equal to the vertical drop (Jackson, 2000). However, their aerodynamic characteristics become particularly interesting at higher angles of attack, where lift coef-

ficients continue to increase without abrupt stall behavior commonly observed in conventional fixed-wing aircraft. This feature has attracted attention in bio-inspired aerodynamic research, especially for low-speed and high-angle-of-attack applications (Bishop, 2006). In this study, the average geometric dimensions of sugar gliders are adopted based on existing experimental and morphological studies. The resulting biomimetic comparison models are illustrated in Figure 2.

2.4 Simulation settings

The first step in this research was to develop a WiG model that accurately represents the intended design for simulation. The model was tested within a rectangular computational domain of varying sizes to evaluate the influence of domain dimensions on simulation results. It was found that while domain size slightly affects the results due to mesh distribution, no strict limitation exists, and adjustments can be made if the domain is excessively large.

For aerodynamic analysis in the ground effect, the key consideration is the lower boundary of the domain, which must move at the same velocity as the airflow to simulate the relative motion between the vehicle and the ground (Bil et al., 2015). The boundary conditions for this study are illustrated in Figure 3.

In this research, the domain was chosen based on the model size and following standard CFD guidelines. The final domain dimensions were: left and right walls 7 m from the wingtip, outlet wall 35 m, inlet wall 15 m, upper wall 8 m, and lower wall 3 m in height relative to the WiG. These dimensions were selected to ensure that the domain is sufficiently large to capture flow phenomena while minimizing computational cost. Before running numerical simulations for lift and drag, several conditions were applied:

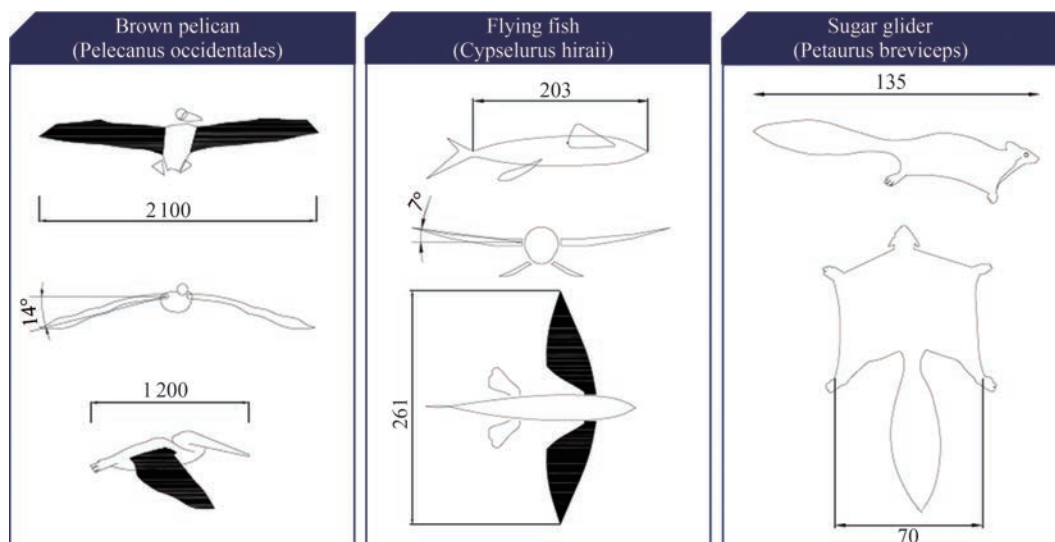


Figure 2 Proposed biomimetic models of WiG craft

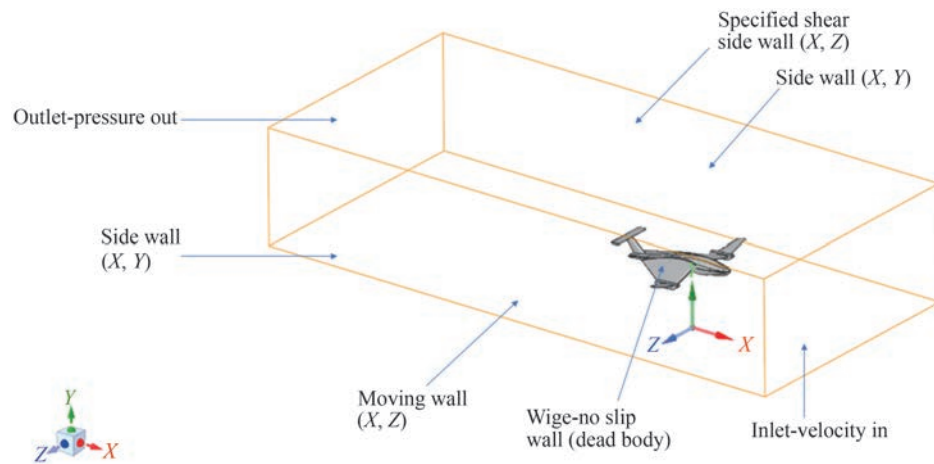


Figure 3 Boundary condition of WiG simulation

- The computational domain must be checked and corrected if necessary at the boundaries.
- The lower boundary acts as a moving wall to account for ground effect.
- Flow above approximately 10 m is considered free from ground effect.
- Simulation models are refined and optimized using ANSYS Fluent.

In the developed simulations, numerous parameters were evaluated using ANSYS Fluent. For comparison, previous studies provide methodological guidance: Bil et al. (2015) used the SST $k-\omega$ turbulence model to investigate aerodynamic conditions of the Seabus SB-8, while Lao and Wong (2018) applied the Spalart–Allmaras model for improved accuracy near the ground effect. Although their objectives differ—Bil focused on overall flow and forces, Lao on Oswald efficiency—both studies provide relevant insights for domain and mesh setup.

Similar CFD approaches have been applied in marine applications by Budiyanto et al. (2020; 2021), analyzing hydrodynamic effects on high-speed vessels with hydrofoil and stern foil configurations. These studies demonstrated that stern foils can reduce total resistance by up to 26.7%, and hydrofoil mounting positions significantly influence lift-to-drag ratios. Such investigations provide an important reference for domain sizing, mesh sensitivity, boundary conditions, and validation of lift and drag in near-surface flows (Syahrudin et al., 2020; Budiyanto et al., 2021). In the present study, the flow regime is characterized using the Reynolds number, which is defined based on the wing chord length and free-stream velocity and is maintained within the same order of magnitude as those reported in previous experimental and numerical WiG and hydrofoil studies to ensure physical relevance. The Reynolds number used in this simulation is $Re = 3.2 \times 10^5$, calculated based on the mean aerodynamic chord. The simulations employed both the Spalart–Allmaras and SST $k-\omega$ turbulence models to enable comparison and selection of

the most appropriate model for WiG analysis. The simulation parameters for the WiG model are summarized in Table 2.

Table 2 Parameter setting used in the numerical simulation of the WiG model

Solver	Fluent ansys
Ambient pressure	1 atm
Air density	1.185 kg/m ³
Turbulence model	Shear stress transport $k-\omega$ model
Gravity	9.8 m/s ²
Reference area	64 m ²
Reference chord	1 m
Moving wall speed	41 m/s
Inlet velocity	41 m/s
Boundary condition	Specified shear pada wall No slip pada WIGE (Wall)

In this study, different mesh quantities were obtained due to the computational domain being adjusted to the geometric size of each aircraft model. The simulations were conducted without employing a Body of Influence, utilizing a poly-hexcore volume mesh configuration with maximum skewness values ranging from 0.08 to 0.20, indicating good mesh quality. The total number of cells varied between approximately 900 000 and 3 million elements, depending on the model and domain size.

To ensure reliability, a mesh independence analysis was performed, confirming that further mesh refinement did not produce significant changes in the aerodynamic coefficients. Moreover, the accuracy and stability of the CFD results were evaluated based on the iteration convergence history presented in Figure 4, which demonstrates consistent residual reduction and stable solution behavior, thereby validating the numerical accuracy of the simulations.

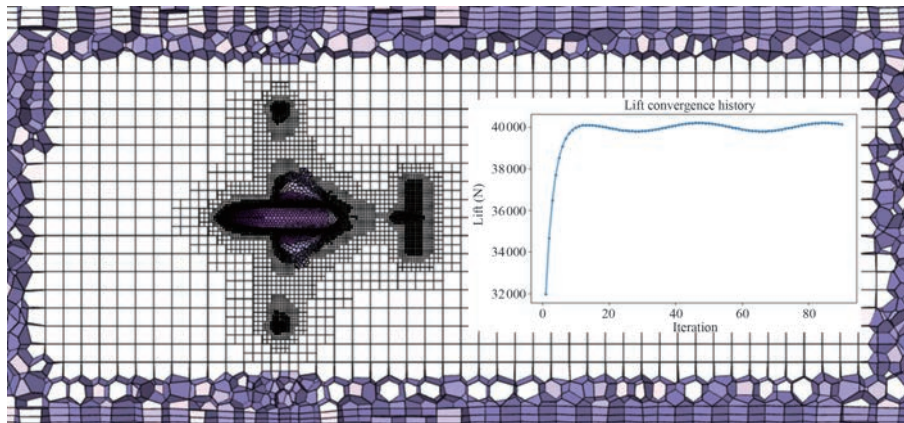


Figure 4 Computational mesh distribution and residual convergence

3 Result and discussion

3.1 Design of WiG

In this study, the WiG design has been designed according to the design requirements. Each model has different characteristics due to its respective Aspect Ratio. By setting the same wing area, the dimension that changes clearly is the wing span. The initial estimate is to adjust to the lift formula which is directly proportional to the wing area so that all have lift that is not much different from each other because of the similar wing profile. However, the lift coefficient of each model will definitely be different due to changes in the chord length and trailing edge.

For the hull and fuselage shape, all models have the same size and shape. The designed the hull model using Maxsurf Modeller to obtain detailed dimensions and additional hydrostatic calculations. The main dimensions of the Wing in ground effect hull are as follows:

- LWL: 11.013 meters
- Beam: 1.668 meters
- Draft: 0.5 meters
- Cb: 0.495
- Cp: 0.602
- Displacement: 4656 kg
- Wetted area: 20.076 m²
- Deadrise: 9.1°

The type of hull is a planning hull which is commonly used on float-planes or other WiGEs without any steps or chines on the bottom because the purpose of its use is still to make prototypes and analysis from the aerodynamic side using Ansys Fluent. The next design stage is the hull, fuselage, and wings are combined through Inventor Professional. The quite proficient need in this modeling software because of its high accuracy and detail. Aspect Ratio is the ratio between the square of the wingspan and the wing area. By equating the wing area for each model, the WiG design results are shown in Figure 5 and Figure 6.

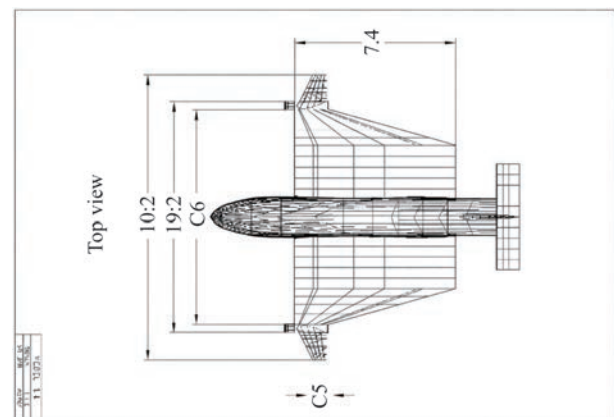


Figure 5 Top view of WiG design model

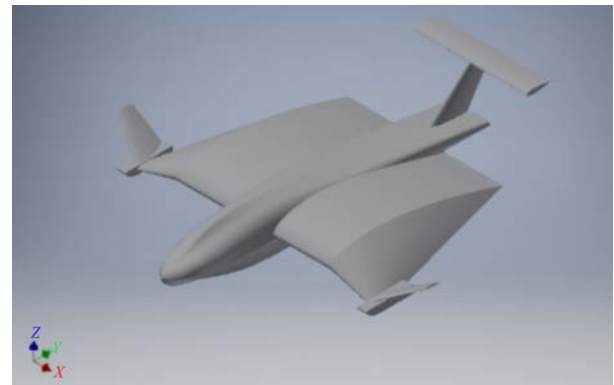


Figure 6 Isometric view of WiG design model

3.2 L/D Ratio analysis

The simulations provided the lift coefficient, drag coefficient, and total pressure acting on the WiG wings. Figure 7 shows the results of airflow simulations for the three proposed biomimetic models: Model 1–Brown Pelican, Model 2–Flying Fish, and Model 3–Sugar Glider. In this study, an angle of attack of 4° was selected because it represents

a typical low-to-moderate incidence at which Wing-in-Ground (WiG) vehicles are designed to cruise, providing sufficient lift with a favorable lift-to-drag ratio while remaining well below the stall margin (Tofa, et al, 2014).

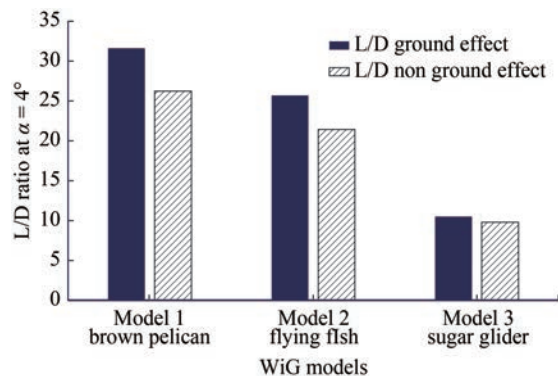


Figure 7 Lift-to-drag ratio of proposed WiG models

The results indicate that Model 1–Brown Pelican achieved the highest lift-to-drag (L/D) ratio within the ground-effect region, demonstrating superior aerodynamic efficiency under these specific conditions. The relatively long wingspan of Model 1 may introduce structural and stability challenges, particularly when operating outside the optimal ground-effect height, where a noticeable reduction in lift is observed. This behavior is consistent with Rozhdestvensky (2006) and Matveev (2003), who reported that while longer wings can enhance lift, they may also complicate stability and control characteristics.

In comparison, Models 2 and 3 exhibit slightly lower L/D ratios but provide more balanced aerodynamic behavior across different operating conditions. Their comparatively moderate wingspans and more stable lift performance suggest improved practical feasibility for real-world WiG applications, supporting the observation by Kim et al. (2018) that moderate lift-to-drag ratios can contribute to more stable and implementable designs. Overall, the comparison highlights the trade-off between maximum aerodynamic efficiency and practical feasibility. While the Flying Fish-inspired model provides the highest L/D ratio, the Brown Pelican and Sugar Glider-inspired models offer better inte-

gration potential into functional WiG prototypes without sacrificing stability or control.

3.3 Analysis of ground effect flow in proposed WiG models

The CFD simulations provide insight into the aerodynamic behavior and ground effect performance of the three proposed biomimetic WiG models: Model 1–Brown Pelican, Model 2–Flying Fish, and Model 3–Sugar Glider. The results are visualized using streamline velocity and pressure contours as shown in Figure 8. The Brown Pelican-inspired design exhibits the most favorable ground effect characteristics among the three models. The streamline patterns indicate smooth airflow beneath the wing, with minimal regions of recirculation and low turbulence intensity. The pressure contours show a balanced distribution along the wing span and fuselage, avoiding excessive pressure peaks that can induce flow separation. These features suggest that Model 1 achieves efficient lift generation with reduced drag, consistent with theoretical expectations of low-aspect-ratio, ground-effect optimized wings (Fish and Lauder, 2011; Triantafyllou and Triantafyllou, 2016). The combination of streamlined flow and moderate pressure gradients contributes to a stable and efficient ground effect, making this model particularly suitable for near-surface flight applications.

The Flying Fish-inspired model shows higher lift in the CFD results, but streamlines beneath the wing are less uniform, with localized areas of recirculation and slightly higher turbulence near the wingtips. Pressure contours indicate more pronounced variations along the wing, which can lead to instability outside the immediate ground effect zone. While this model offers excellent lift-to-drag ratio, the complex flow patterns and extended wingspan may introduce challenges in practical vehicle design, especially for maintaining stability in variable sea conditions (Matveev, 2003). The Sugar Glider-inspired WiG shows intermediate performance. Streamlines are reasonably smooth, but there is slightly higher turbulence near the wing root and mid-span compared to Model 1. Pressure distribution is relatively uniform, but lift generation is lower, reflecting

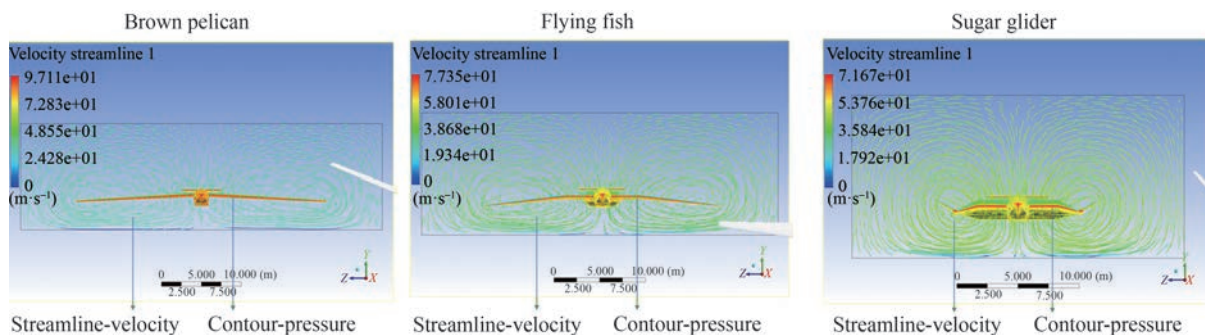


Figure 8 CFD simulation of ground effect flow for the proposed biomimetic WiG models

the smaller wing area and glide-oriented morphology. This model offers a compromise between aerodynamic efficiency and compact wing design, which may be advantageous for maneuverability and structural simplicity (Bishop, 2006; Kim et al., 2018).

Overall, Model 1 (Brown Pelican) demonstrates the most effective ground effect behavior, combining smooth streamline flow, minimal turbulence, and balanced pressure distribution, which leads to efficient lift generation and stable operation near the surface. The comparative analysis highlights the importance of wing morphology and pressure distribution in optimizing near-surface flight performance. Models 2 and 3 offer useful insights into trade-offs between lift efficiency, stability, and practicality, providing a foundation for future WiG design improvements.

4 Conclusions

This study presented a biomimetic-based aerodynamic assessment of wing-in-ground (WiG) configurations inspired by flying animals, including birds and mammals, using computational fluid dynamics (CFD). Each proposed model was developed by translating biological characteristics—such as body size, wing geometry, and flight behavior—into engineering design parameters relevant to near-surface flight. The results demonstrate that each biomimetic model exhibits distinct aerodynamic performance aligned with its biological inspiration. The brown pelican-inspired configuration (Model 1) achieved the highest lift force, reaching approximately 68 kN. This performance is attributed to its relatively larger body size and wing characteristics, which are naturally adapted for efficient lift generation and high-speed maneuvering close to the surface. In contrast, the sugar glider-inspired configuration (Model 3) generated the lowest lift, approximately 37 kN, reflecting its biological adaptation for short-distance, low-altitude gliding with light-weight body mass and membrane-supported wings. The results highlight the inherent aerodynamic limitations of gliding mammals compared to birds, particularly in terms of sustained lift generation and maneuverability.

Overall, the findings confirm that biomimicry offers a rational and effective framework for the preliminary design of WiG craft, where aerodynamic performance can be systematically tailored by adopting biological flight strategies. Further work will focus on refining the geometrical parameters, extending the operational envelope, and conducting wind tunnel or prototype testing to validate the numerical predictions and enhance the practical applicability of biomimetic WiG designs.

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