PHILIPPINE SCIENCE HIGH SCHOOL
Southern Mindanao Campus

Biomimicry in Aeronautics:

Studying Fly Wing Characteristics to Improve Ornithopter Aerodynamics

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Science Fair 2023 Write Up

Biology I, Chemistry I, Physics I, and Computer Science III

I. Objectives

1. To analyze the structure and composition of fly wings.
2. To deduce the advantages and disadvantages of ornithopter wings modeled after fly wings.
3. To apply fly-inspired ornithopters in the context of geology and security in the Philippines.

II. Introduction

Flying is now possible as a result of technological advancements. The Wright brothers invented the first airplane, and Russia was the first country to send astronauts outside the planet in a spaceship. The French invented ornithopters in the 1870s; they are aircraft that fly by flapping their wings and are inspired by birds.

Figure 1. *Ornithopter (The Ornithopter Society, n.d.).*

Micro-unmanned ornithopters have been critical in the surveillance of people and terrain, despite receiving little attention (The Ornithopter Society, n.d.). Locally, flapping-wing micro-air vehicles (FWMAVs) could aid in the surveillance of seismic areas, forest degradation due to climate change, and difficult terrain, such as mountains where Filipino trekkers have perished.

In a recent study by Zhang et al. (2023), the design and aerodynamics of FWMAVs were analyzed, including the currently-popular DelFly Nimble (Figure 2), inspired by fruit flies. This review showcased how mimicking fly wing characteristics in the innovation of ornithopters stems from biology, chemistry, and physics.

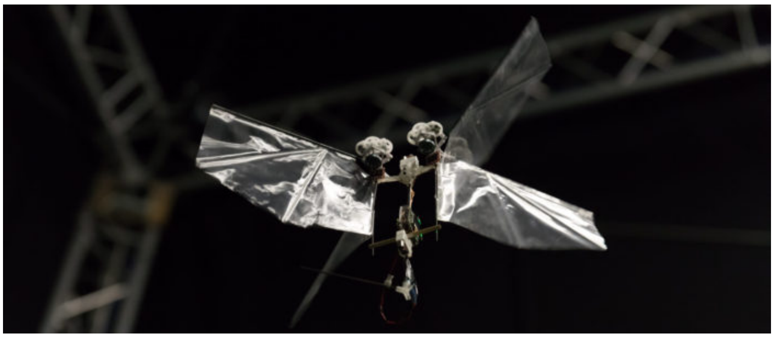

Figure 2. *DelFly Nimble in hover (DelFly, n.d.).*

III. Science Concepts Involved

Biology

This study centers on biomimicry – the science of mimicking and applying structures and mechanisms from organisms in nature to create efficient man-made designs. The netting patterns of spiderwebs, for example, have been copied onto glass windows to deter birds from colliding. The chemical composition of leaves has also influenced the development of long-lasting foams and plastics. Even the dynamics of an Australian forest have been used to establish sustainable factories (Biomimicry 2.8, n.d.). The overall anatomy and structure of fly wings were studied and deemed fit to be mimicked onto ornithopter wings.

The features of fly wings, which were applied in the DelFly Nimble, have evolved over time to maximize aerodynamic efficiency: flexibility, shape, frequency, and stroke (Krishna et al., 2020).

Fly wings are mostly made of chitin, a polysaccharide that is thin and elastic but durable (this will be further discussed in the Chemistry section) (Hou et al., 2021). However, these wings also require some structure and rigidity. Veins and sensory receptors such as campaniform sensilla, inverted bristles, and afferent nerves provide structural support while keeping weight to a minimum. Also, wing membranes are active aerodynamic surfaces composed of multiple layers of cuticle of varying thickness that form fine geometrical structures known as wing corrugation. This wing corrugation increases stiffness, preventing wing deformation during flight. The scale of these structures is much smaller than that of wing primary flow structures, such as wing tips and leading edge vortices, so that flight is not interfered with. Fly wings are finely tuned structures that allow them to fly with strength and endurance in general (Krishna et al., 2020).

Moreover, fly wings have a tapered shape, similar to Figure 3; the wing is thinner at its end. This allows the balancing of the four flight forces to be discussed in the Physics section. Because of this shape and the semi-flexible structure of fly wings, flies are able to flap their wings at high frequencies and maintain a rotating stroke of flapping, helping them fly fast, turn sharply, and hover in a stable manner (Krishna et al., 2020). In a broad sense, being able to fly efficiently is crucial to the flies' survival. They are able to evade predators, reproduce in hard-to-find crevices, and latch onto food.

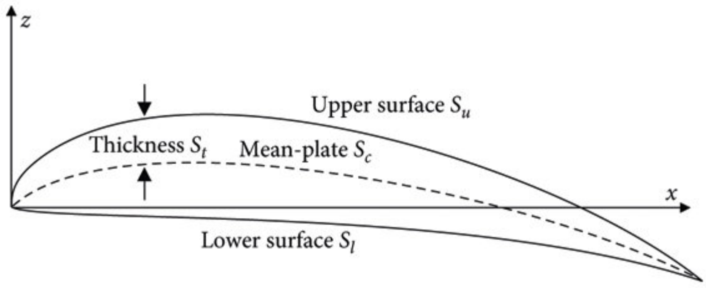

Figure 3. *Wing thickness and surface diagram (Xu et al., 2020).*

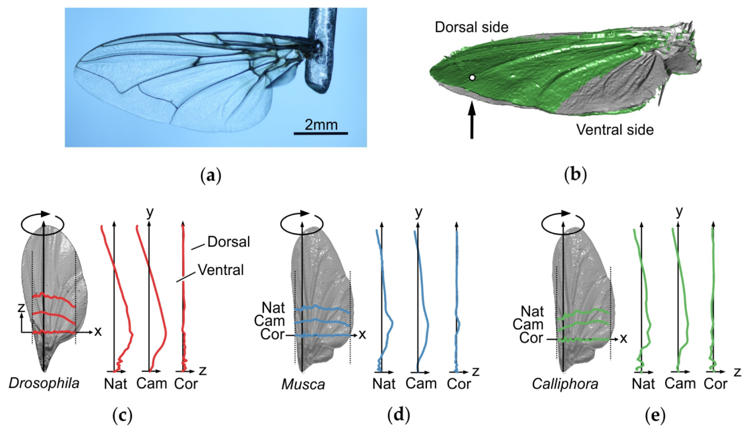

Figure 4. *Varying fly wings' structures (a) detached blowfly Calliphora vomitoria wing (b) blowfly wing deformation (green-shaded) after being subjected to an amount of force (c-e) Drosophila melanogaster, Musca domestica, and Calliphora vomitoria wing profiles (Krishna et al., 2020).*

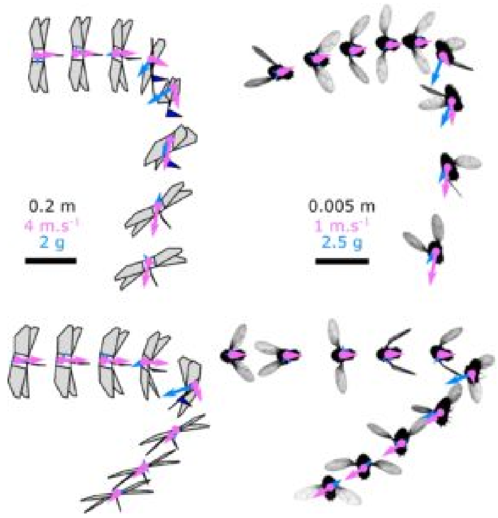

Figure 5. *Flight turn comparison between the DelFly Nimble (left) and a fruit fly (right) (DelFly, n.d.).*

Chemistry

In designing wings for FWMAVs, chemical composition is vital. The DelFly Nimble's wings are made of polyethylene terephthalate (PET), which is a thin but tension-resistant polyester film used commercially (The Index Project, n.d.). Its molecular structure is shown in Figure 6.

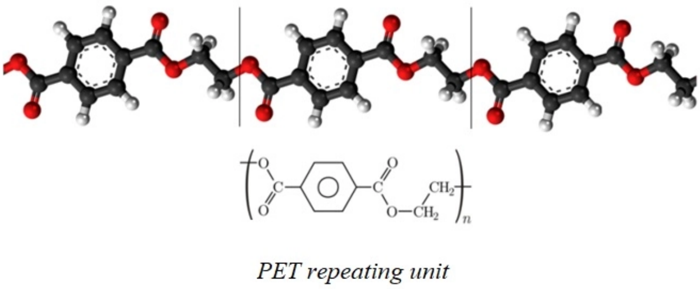

Figure 6. *Molecular structure of polyethylene terephthalate (Omnexus, n.d.).*

This structure shows that PET possesses hydrogen bonding, one of the strongest intermolecular forces. Hydrogen bonding exists between hydrogen and nitrogen, oxygen, or fluorine (Purdue University, n.d.). In PET, hydrogen can bond with oxygen, contributing to the high tensile strength of the polyester film.

More than that, a unit of PET also contains an aromatic ring with six carbon atoms, another influencing factor in the material's durability (Britannica, 2023). Aromatic rings are joined by covalent bonds, which involve the sharing of valence electrons between atoms. Therefore, this maximizes the force of attraction between the positively-charged protons in the nuclei and the negatively-charged valence electrons, holding the molecule firmly intact (Carey, 2008).

The usage of PET was inspired by the material that fly wings are mainly composed of – chitin (Krishna et al., 2020). This abundant natural polymer is similarly thin and flexible but durable. It is a polysaccharide containing an acetyl amine group made of 2 carbons, 3 hydrogens, 1 oxygen, and 1 nitrogen and a hydroxyl group made of 1 oxygen and 1 carbon (Hou et al., 2021; National Cancer Institute, n.d.; Klecker & Nair, 2017; Block & Smith, 2018). The hydrogens of the acetylamine group and oxygen of the hydroxyl group interact through hydrogen bonding, giving chitin its strength (Hou et al., 2021).

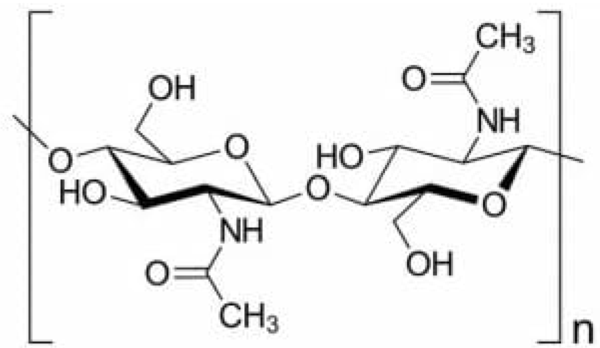

Figure 7. *Chitin structure (BD Editors, 2017).*

(a)

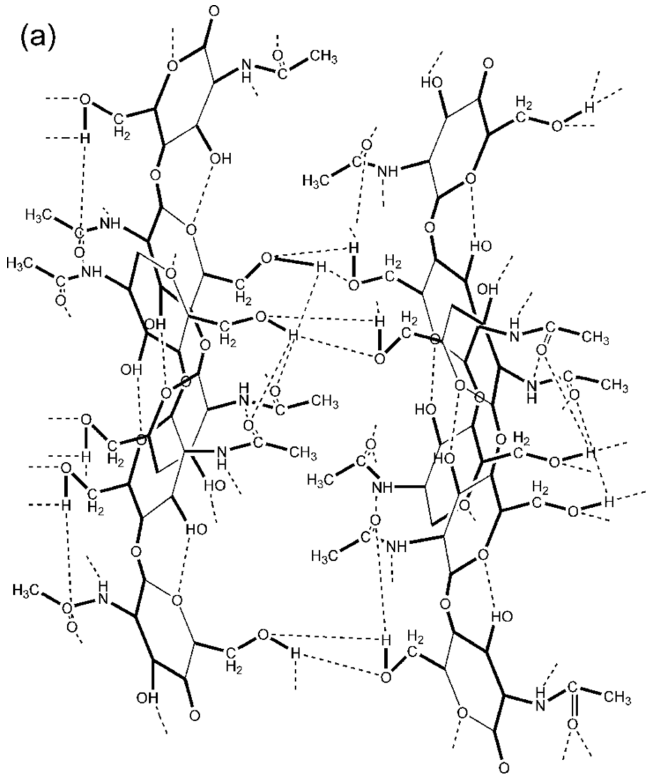

Figure 8. *Molecular structure and hydrogen bonding in (a)-chitin and (b)-chitin (reproduced from Ref. [51] by permission of Elsevier Science, Amsterdam) (Pillai et al., 2009).*

Physics

The Theory of Flight is the basis of the functionalities of the DelFly Nimble. This theory involves four vectors: the horizontal forces, thrust and drag, and the vertical forces, lift and weight (Figure 9). In order for heavier-than-air objects—birds, airplanes, and butterflies—to fly, these forces must be balanced (MIT Department of Aeronautics and Astronautics, 1997).

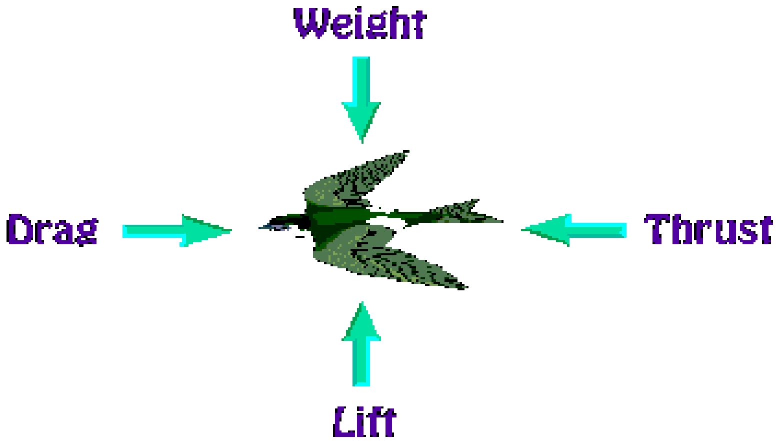

Figure 8. *Four physical forces of flight (MIT Department of Aeronautics and Astronautics, 1997).*

Thrust is the force of propulsion that launches a flying object where the vector is directed. It can be computed through Newton's second law of motion:

$$\mathbf{F = ma}$$

where thrust (F) is the product of mass (m) and acceleration (a) (MIT Department of Aeronautics and Astronautics, 1997).

On the other hand, drag opposes thrust, which is otherwise air resistance in flight. It is given in the equation below:

$$\mathbf{D = (C_D)(\tfrac{1}{2}\rho v^2)(A)}$$

where drag is the product of the coefficient of drag (C_D), half of the density (ρ) times the squared velocity (v^2), and the area of reference (A) (MIT Department of Aeronautics and Astronautics, 1997).

Onto the vertical components, lift is the upward force. It pushes an object afloat, using differences in pressure made through airfoils, which are intricately shaped structures of the aircraft. When air flows faster above the airfoil, the pressure in that part will decrease, causing the pressure below to generate lift (Figure 9). The equation of lift is:

$$\mathbf{L = (C_L)(\tfrac{1}{2}\rho v^2)(S)}$$

where lift (L) is the product of the coefficient of lift (C_L), half of the density (ρ) times the squared velocity (v^2), and the wing area (S) (MIT Department of Aeronautics and Astronautics, 1997).

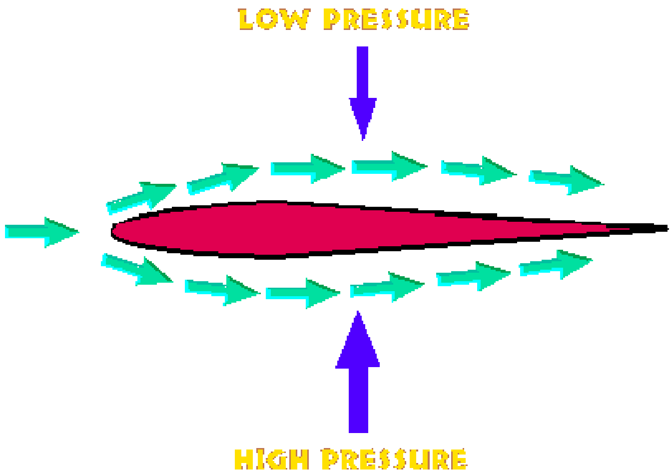

Figure 9. *Difference of pressure over an airfoil in lift generation (MIT Department of Aeronautics and Astronautics, 1997).*

The second vertical force is weight. It points downward, opposite to the direction of lift. Weight determines the heaviness of an object with respect to the gravitational field strength of a celestial body, like Earth:

$$\mathbf{W = mg}$$

where weight (W) is the product of mass (m) and the gravitational field strength of a given celestial body (g) (MIT Department of Aeronautics and Astronautics, 1997).

By principle, thrust should exceed drag, while lift should exceed weight. The lesser the drag and the higher the lift, the more efficient an aircraft is. And the DelFly Nimble showcases these principles through its fly-inspired design.

The DelFly Nimble has a thrust-to-weight ratio of 1.3, with its weight being only 29 g. Moreover, its lift generation exceeds its weight not only because of how lightweight it is but also because of its flexible wings made of the polyester film PET mentioned above (DelFly, n.d.).

In an experiment by Reid et al. (2019), it was found that flexible wings were more effective in lift generation than rigid wings. The researchers used a custom-made flapper based on *Manduca quinquemaculata* (five-spotted hawk moth) to measure wing-driving torques and angular position.

The obtained results show that, across the range of natural frequencies, flexible wings require less energy to flap and generate lift compared to rigid wings.

At a flapping frequency of 79 Hz, the wing flexibility shows a reduction in energetic costs by as much as 25%. From 60-90 Hz, the flexible wing requires 60% more maximum twisting forces and approximately 15% more maximum positive energy output than the rigid wing. This suggests a potential trade-off between maximum force generation and overall efficiency (Reid et al., 2019).

Assuming the insect weighs between 1.5-2.5 g and both wings are flapping symmetrically, the mass-normalized peak power is between 46-77 W/kg for the rigid wing and 75-125 W/kg for the flexible wing; the flexible wing produces more power for its weight. It is further estimated that the flexible wing can store approximately 30% of the total energy required over a wingbeat (Reid et al., 2019).

IV. Application

FWMAVs like the DelFly Nimble can be used in biology and geology field research, search and rescue, and surveillance and reconnaissance (The Ornithopter Society, n.d.). This potential comes from how the DelFly can carry a load of up to 4 g, which a micro camera suffices (DelFly, n.d.).

The Philippines is home to many active volcanoes and faults. Roughly 60% and 74% of the country's land and population, respectively, are exposed to the brunt of natural disasters like earthquakes and volcanic activity. In 2020, the key natural hazard was volcanic activity, affecting more than 700,000 Filipinos (Climate Change Knowledge Portal, 2021). Just recently, the Department of Science and Technology (DOST) called for the Philippine Institute of Volcanology and Seismology to make room for more equipment in order to maximize its monitoring of tectonic activity, especially given that in the past decade, several strong earthquakes have claimed the lives of thousands (De Vera, 2023). With this, FWMAVs could help concerned governmental agencies survey faults, volcanoes, and affected areas. It could be a lightweight and energy-efficient solution to monitoring seismic developments or the damage inflicted by these developments.

Another application for the FWMAVs is search and rescue. There have been cases in the Philippines where trekkers have gotten lost in the mountains (Lasco, 2015). With FWMAVs, searches could be done quicker and rescues could be done on time. Mountains are home to various hazards, such as wild animals, ditches, and ravines, which have claimed the lives of many hikers (Lauro, 2022).

Lastly, FWMAVs could be used for military surveillance. In the 1970s, the United States developed a tiny ornithopter mimicking a dragonfly to spy on civilians; however, it was discarded because it flew for only a minute and had ineffective control mechanisms (The Ornithopter Society, n.d.). Nevertheless, this shows the potential of FWMAVs as military equipment during wars. For example, in the Marawi Siege, the perpetrators were settled in tight hideouts, making it hard for the military to monitor movement (Hincks, n.d.). But with FWMAVs crafted to look and sound like real insects, monitoring could be made safer.

The applications listed above only scratch the surface of the potential of FWMAVs. There are also limitations that should be considered, such as battery life and runtime; however, the possible uses of these vehicles modeled from flies call for more research, discussion, and focus on this topic.

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