Aerodynamics of Birds' Flight: Analysis and Applications

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Abstract: The problem of drag and lift optimization is one underlying problem in the field of aerodynamics, aviation and aeronautical science. Mankind for centuries has sought to study nature and to apply relevant information obtained to solve myriads of flight problems. The research was actualized by carrying out investigation on the way the very masters of flight (birds) navigate effortlessly through the air. The problem of flapping was considered on flight condition. A flapping aircraft was thereafter modelled and simulated. A flapping frequency of 1.2 Hertz was designed and arrived at using a wingspan of 1.2 meters. The pressure distribution obtained was between $-2.71x10^{1}$ Pascal to $1.24x10^{1}$ Pascal and the velocity $9.86x10^{-3}$ m/s to $8.98m/s$ on the aircraft. The results generated have provided additional information for aerodynamics, aviation and aeronautical science for improvement on flight condition.

Keywords: Aerodynamics, Birds' flight, applications, flapping frequency, flight modeling, simulation.

1.0 Introduction

In man's constant quest to subdue the earth and dominate it which is by no means a divine mandate, humans have sought all kinds of ways and means to optimize processes, solve problems and hence be masters of the world they inhabit. Science and technology in its quest to observe the laws that govern nature and hence help humanity to manipulate the various constraints and elements to its benefit has been an ever expanding pool and body of knowledge. One of such branches of science and physics is aerodynamics. According to Cengel, "aerodynamics is application of fluid dynamics to air, land and water-going vehicles. Often the term is specifically applied to the flow surrounding, and forces and moments and on flight vehicles in air as opposed to vehicles in water and other liquids [1]. Alternatively, "Aerodynamics is the study of forces and the resulting motion of objects through the air [2].

Birds on the other hand asides various insects and mammals are the masters of flight. Man for centuries in his innovative nature has pommeled the forces of nature to do his will by traversing land travel and sea travel but even in the advent of the industrial revolution man could not subdue the force of wind and gravity as a means of transportation. The Wright brothers however came along in the late nineteenth and early twentieth century to reverse that trend and hence break the deadlock. In the midst of so much extensive study and observance, they eventually designed and manufactured the first working and man-made device to overcome the force of gravity and hence set the pace for any future innovations in flight and air travel. However due to the in-depth, ever widening and progressive nature of modern science and technology, it becomes imperative for the scientists and engineers to carry out further research in order to discover the possible innovations that can be applied to what is already on ground.

The term aerodynamics is often used synonymously with gas dynamics, the difference being that "gas dynamics" applies to the study of the motion of all gases, and is not limited to air. The formal study of aerodynamics began in the modern sense in the eighteenth century, although observations of fundamental concepts such as aerodynamic drag were recorded much earlier. Most of the early efforts in aerodynamics were directed toward achieving heavier-than-air flight, which was first demonstrated by Otto Lilienthal in 1891. Since then, the use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations has formed a rational basis for the development of heavier-than-air flight and a number of other technologies. Recent work in aerodynamics has focused on issues related to compressible flow, turbulence, and boundary layers and has become increasingly computational in nature.

In 1799, Sir George Cayley became the first person to identify the four aerodynamic forces of flight (weight, lift, drag, and thrust), as well as the relationships between them, and in doing so outlined the path toward achieving heavier-than-air flight for the next century. Weight is represented by the symbol; W, lift; F_L, drag; F_D, and thrust by the symbol; T. One important branch of fluid mechanics relevant to this research topic is Computational fluid dynamics (CFD). "Computational fluid dynamics (CFD) began as an effort to solve for flow properties around complex objects and has rapidly grown to the point where entire aircraft can be designed using computer software, with wind-tunnel tests followed by flight tests to confirm the computer predictions. Understanding of supersonic and hypersonic aerodynamics has matured since the 1960s, and the goals of aerodynamicists have shifted from the behaviour of fluid flow to the engineering of a vehicle such that it interacts predictably with the fluid flow. Designing aircraft for supersonic and hypersonic conditions, as well as the desire to improve the aerodynamic efficiency of current aircraft and propulsion systems, continues to motivate new research in aerodynamics, while work continues to be done on important problems in basic aerodynamic theory related to flow turbulence and the existence and uniqueness of analytical solutions to the Navier-Stokes equations.

The Navier Stokes equation is one very essential equation in the field of fluid dynamics. It can be used to model fluid flows over a variety of cross-sections and since air is the fluid of concern in this case, the equation comes in handy for aerodynamic analysis.

"Although the modern theory of aerodynamic science did not emerge until the 18th century, its foundations began to emerge in ancient times. The fundamental aerodynamics continuity assumption has its origins in Aristotle's Treatise on the Heavens, although Archimedes, working in the 3rd century BC, was the first person to formally assert that a fluid could be treated as a continuum"[3]. "Archimedes also introduced the concept that fluid flow was driven by a pressure gradient within the fluid. This idea would later prove fundamental to the understanding of fluid flow. In 1687, Newton's *Principia* presented Newton's laws of motion, the first complete theoretical approach to understanding mechanical phenomena. In particular, Newton's second law, a statement of the conservation of momentum, is one of three fundamental physical principles used to obtain the Euler equations and Navier-Stokes equations.

In 1738, the Dutch-Swiss mathematician Daniel Bernoulli published *Hydrodynamica*, in which he described the fundamental relationship between pressure and velocity, known today as Bernoulli's principle. This states that the pressure of a flowing fluid decreases as its velocity increases and as such was a significant early advance in the theory of fluid dynamics, and was first quantified in an equation derived by Leonhard Euler [3].

Bernoulli's Equation ignores compressibility of the fluid, as well as the effects of gravity and viscous forces on the flow. Leonhard Euler would go on to publish the Euler equations in 1757, which are valid for both compressible and incompressible flows. The Euler equations were extended to incorporate the effects of viscosity in the first half of the 1800s, resulting in the Navier-Stokes equations. Bernoulli's principle can be used to calculate the lift force on an airfoil, if the behavior of the fluid flow in the vicinity of the foil is known. For example, if the air flowing past the top surface of an aircraft wing is moving faster than the air flowing past the bottom surface, then Bernoulli's principle implies that the pressure on the surfaces of the wing will be lower above than below. This pressure difference results in an upwards lifting force [4]. Whenever the distribution of speed past the top and bottom surfaces of a wing is known, the lift forces can be calculated (to a good approximation) using Bernoulli's equations, which were established by Bernoulli over a century before the first man-made wings were used for the purpose of flight [5].

In his 1738 publication *Hydrodynamica*, Daniel Bernoulli described a fundamental relationship between pressure, velocity, and density, now termed Bernoulli's principle, which provides one method of explaining lift.

Aerodynamics work throughout the 19th century sought to achieve heavier-than-air flight. George Cayley developed the concept of the modern fixed-wing aircraft in 1799, and in doing so identified the four fundamental forces of flight - lift, thrust, drag, and weight. The development of reasonable predictions of the thrust needed to power flight in conjunction with the development of high-lift, low-drag airfoils paved the way for the first powered flight. On December 17, 1903, Wilbur and Orville Wright flew the first successful powered aircraft. The flight, and the publicity it received, led to more organized collaboration between aviators and aerodynamicists, leading the way to modern aerodynamics.

Theoretical advances in aerodynamics were made parallel to practical ones. The relationship described by Bernoulli was found to be valid only for incompressible, inviscid flow. In 1757, Leonhard Euler published the Euler equations, extending Bernoulli's principle to the compressible flow regime. In the early 19th century, the development of the Navier-Stokes equations extended the Euler equations to account for viscous effects. During the time of the first flights, several investigators developed independent theories connecting flow circulation to lift. Ludwig Prandtl became one of the first people to investigate boundary layers during this time.

Four basic forces are responsible for and involved in the flight process and activity of birds and hence aircraft. There are; trust, drag, lift or upward force and weight.

These forces are illustrated in Figure 1.

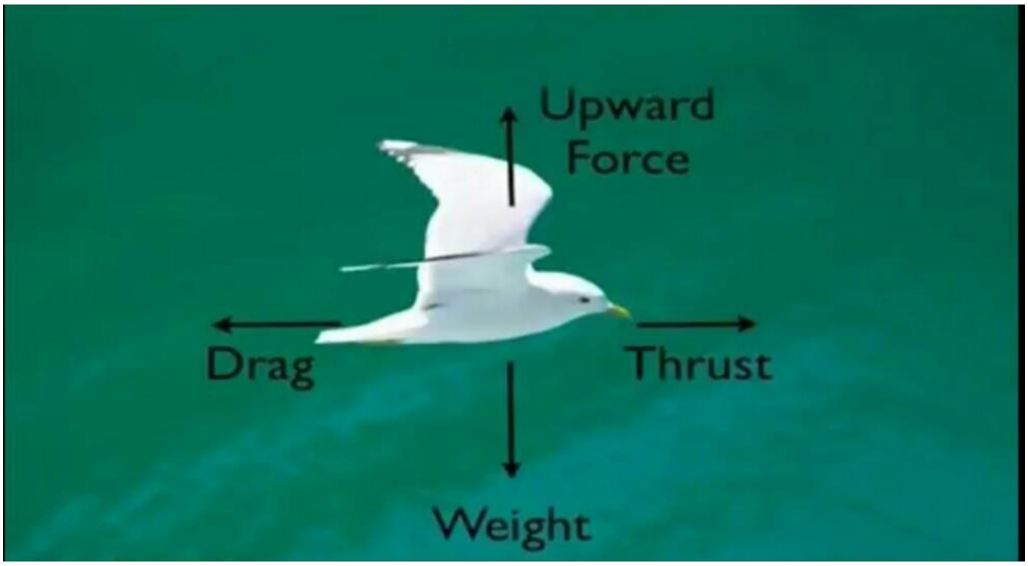


Figure 1: A visual representation of forces acting on a bird while in flight [6]

Usually, the shape of a bird’s wing is what fluid mechanics refers to as an AIRFOIL SHAPE. This shape is very crucial to the ability of any organism or man-made structure to lift itself off the ground and fly. Though they vary in shape and outline. Broadly speaking there are two types of air foils. Symmetrical and non-symmetrical. Every other type is a subset of these two aforementioned types. A sample of this shape is given below in Figure 2.

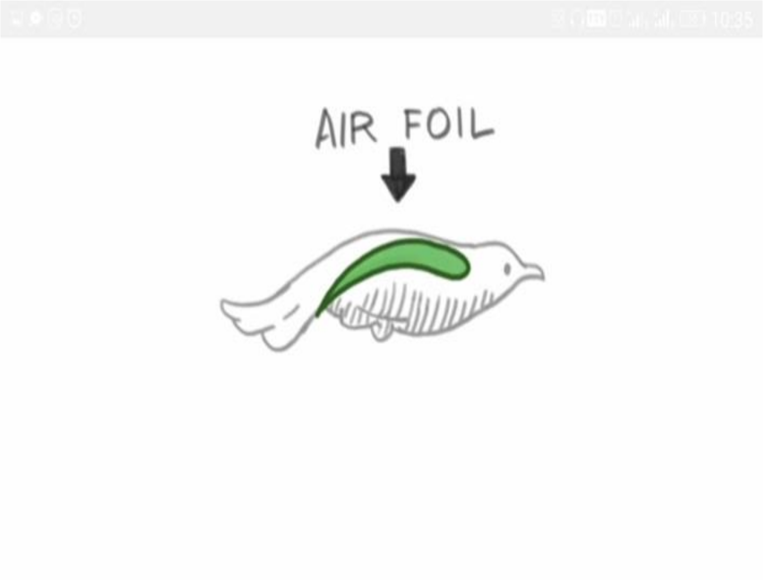
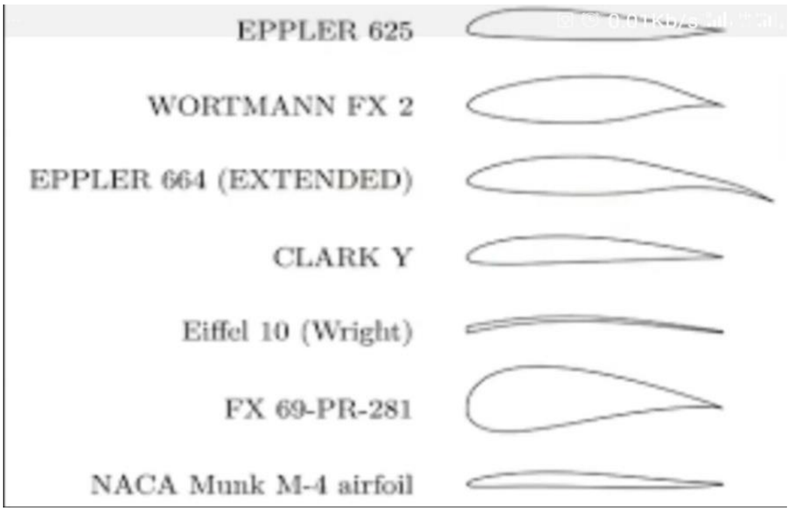


Figure 2: The basic shape of an airfoil [7]

As is evident from the above illustration, "the curved upper surface constricts the flow of air more than the flatter lower surface, causing the air above the wing to speed up more than the air below. The faster the air speeds up, the lower its pressure becomes. So, the faster moving air above has less pressure than the slower moving air below.

The higher air pressure below pushes the wing up [8]. This results in the lift force that also results in the total raising of the body to overcome gravity. The institute continues "Any further increase in the speed of air will increase the difference in pressure and increase the lifting force on the wing [8]. A practical application of Newton's third law is very evident in an airfoil as the high pressure exerted by air molecules on the wing is redirected to the ground underneath the plane or bird which in turn serves as a lift mechanism for the flying body.

Airfoils and bird wings take different shapes and configurations as situation demands. Figure 3 gives a layout of the different airfoil types.



(a)

(b)

Figure 3 (a) and (b): **Different airfoil configurations by name and code [9]**

Thrust is the force needed to overcome the resistance of air (drag) to the passage of an aircraft. To maintain level flight at constant speed, constant thrust is required; to climb or descend the aircraft whilst maintaining constant speed, the thrust must be increased or decreased; to increase or reduce the speed of the aircraft whilst maintaining level flight, the thrust must be increased or decreased.

In an aircraft, the thrust is generated in different ways according to the type of propulsion:

(i) Turbojet: all the thrust is generated in the form of jet efflux from the rear of the engine. (Now used mostly in military aircraft).
(ii) Turbofan: Most of the thrust is generated by a large fan at the front of the engine; a small percentage is generated by jet efflux.
(iii) Turboprop: Most of the thrust is generated by the propeller; a small percentage is generated by jet efflux.
(iv) Piston: All the thrust is generated by the propeller.

The Power required to generate thrust depends on a number of factors, but in simple terms it may be said that the power is proportional to the thrust required times the aircraft speed.

Drag is the force that a flowing fluid exerts on a body in the flow direction [1] He continues " Drag is usually an undesirable effect, like friction, and we do our best to minimize it. Reduction of drag is closely associated with the reduction of fuel consumption in automobiles, submarines, and aircraft; improved safety and durability of structures subjected to high winds; and reduction of noise and vibration. But in some cases, drag produces a very beneficial effect and we try to maximize it.[1] also in Houghton and Carpenter's words, "this (drag) is the component of force acting in the opposite direction to the line of flight, or in the same direction as the motion of the undisturbed stream. It is the force that resists the motion of the aircraft."[8] In other words drag and friction are analogous to one another. Drag can be measured and calculated using a formula called drag coefficient formula. The coefficient of drag is written symbolically as C_D.

This is the component of force acting upwards, perpendicular to the direction of flight or of the undisturbed stream [8]. In Cengel's words, it is "the net aerodynamic force on an object perpendicular to the motion of the object." [1]. It is that component of a flight force that enables the bird or aerial vehicle to be able to take off (get itself up off from the ground). It can be measured using the lift coefficient, C_L.

Weight is the force with which gravity attracts a body toward the center of the Earth. It is a product of the mass of a body and the acceleration acting on the body. If the weight of the bird or body is greater than the lift generated, flight is impossible. Weight is there major factor in aircraft construction and operation and demands respect from all engineers involved and pilots as well.

Additionally, though the scope of this work does not focus on that, a good grasp of fluid mechanics topics like boundary layer theorem, Newton's laws of motion particularly the third one (law of action and reaction) and dimensional analysis is very much in handy when studies on heavier than air flight but also other fluid flow problems are initiated like sea and underwater travel.

Angle of attack is the angle between an airfoil or wing and the free-stream flow velocity vector. High angles of attack tend to produce high lift and lift coefficients. However, at angles of 15° and above, a phenomena called stall occurs which decreases lift and can affect the bird or plane speed.

[8], the aspect ratio is a measure of the narrowness of the wing planform. It is a measure of how relatively narrow an airfoil is in the flow direction. Mathematically, the aspect ratio of a wing is the ratio of its span to its mean chord. It is equal to the square of the wingspan divided by the wing area. Thus, a long, narrow wing has a high aspect ratio, whereas a short, wide wing has a low aspect ratio.

The Glide ratio of an aircraft is the distance of forward travel divided by the altitude lost in that distance. Planform area is the area of the wing from the top view. Drag coefficients are used to quantify the resistance of an object particularly birds and aircraft in this context as it moves through a fluid. They are a dimensionless quantity and allow aerodynamicists to account for the influence of shape, inclination and flow conditions when calculating aerodynamic drag.

The lift coefficient is a dimensionless coefficient that relates the lift generated by a lifting body to the fluid density around the body, the fluid velocity and an associated reference area.

The chord is an imaginary straight line joining the leading edge and trailing edge of an aerofoil.

The chord length is the distance between the trailing edge and the point where the chord intersects the leading edge. The leading edge of an airfoil surface such as a wing of a bird or aircraft is its foremost edge and is therefore the part which first meets the oncoming air.

The trailing edge of an aerodynamic surface such as a wing is its rear edge, where the airflow separated by the leading edge meets. Essential flight control surfaces are attached here to control the direction of the departing air flow, and exert a controlling force on the aircraft.

The Wing span is the entire length of a bird's or airplane's wings from one tip to the other. The lift-to-drag ratio is the amount of lift generated by a wing or vehicle, divided by the drag it creates by moving through the air. A higher or more favourable L/D ratio is typically one of the major goals in aircraft design. It is the primary measure of aerodynamic efficiency.

Stall is an aerodynamic condition whereby air can no longer smoothly flow over an airfoil, resulting in a rapid loss of lift. It is usually brought about by exceeding the critical angle of attack. Induced Drag is an inevitable consequence of lift and is produced by the passage of an aerofoil (e.g., wing or tailplane) through the air. Air flowing over the top of a wing tends to flow inwards because the decreased pressure over the top surface is less than the pressure outside the wing tip.

Form Drag, also known as Pressure Drag or Profile Drag, is the drag caused by the separation of the boundary layer from a surface and the wake created by that separation. It is primarily dependent upon the shape of the object. Parasite or Parasitic drag, also known as profile drag, is a type of aerodynamic drag that acts on any object when the object is moving through a fluid. Parasitic drag is a combination of form drag and skin friction drag. It affects all objects regardless of whether they are capable of generating lift. Viscous drag is the drag force felt by an object moving through a fluid due to the viscosity of the fluid. Viscosity is an innate property of fluids, and, as an object moves through a fluid, this innate property can either help or hinder the motion of the object. A vortex is a rotating column of air, similar to a tornado. Vortices form behind any wing or body that generates positive or negative aerodynamic lift. In the case of an airplane wing, the total pressure below the wing is larger than the total pressure above the wing.

Bird wings can be broadly classified into four types. They are: Delta wings, Delta wings, Long Soaring wings, Slotted wings (High aspect ratio), Elliptical wings

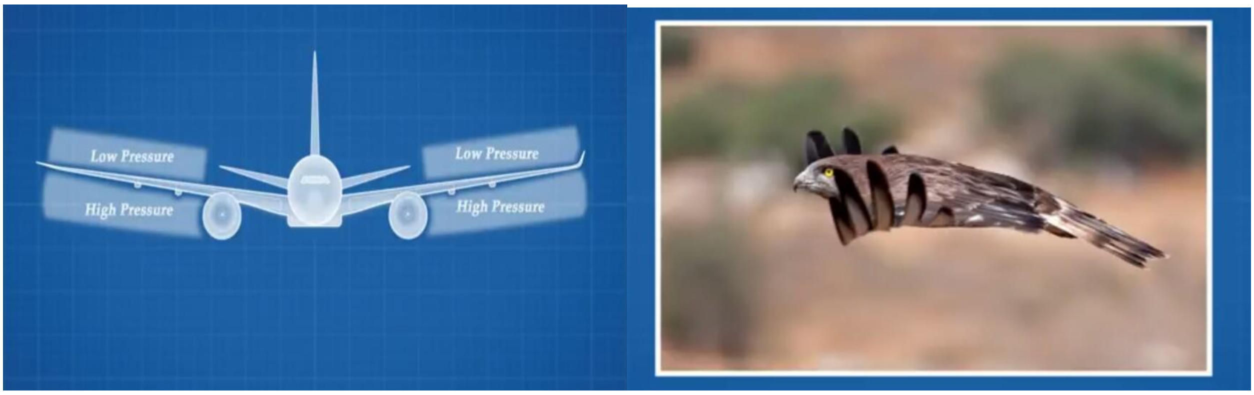
Table 1 shows wing types, properties, advantages and disadvantages as well as application.

Table 1: Wing Types and their Applications

S/N	Name	Types of Bird	Properties	Advantages	Disadvantages	Application/Adaptation
1	Delta wings	Swallows and Peregrine falcons	High speed wings Short and Streamlined in shape Slender and pointed wing tips Swept backwards	Low induced drag Easy control and maneuverability At low speed conditions they can produce a lot of additional lift when placed at high angle of attack, due to the leading edge vortices. Delta wing aircraft do not require a horizontal tail.	At high angles of attack, this wing in practice is susceptible to high induced drag which could lead to stall In practice, angle of attack is limited by tail clearance. It is unable to trim out nose down pitching movement caused by the flaps. Lift induced drag is very high in subsonic conditions. Higher viscous drag due to the large wing area.	Used in fighter jets and high speed planes e.g. Northrop Grumman B-2 Spirit Stealth Bomber
2	Long soaring wings	Albatross, Kestrel, turnstone.	Narrow and very long wings(could be up to 11 feet[3.35metres]) Thin and well streamlined wings	Long protracted and soaring flights Low drag Low turbulence Dynamic soaring	Can't carry much weight/extra load due to low wing loading Difficult landing and take off Difficult to	Gliders

					control and maneuver They can be very slow in flight as they are largely dependent on the wind current and breeze	
3	High aspect ratio wings (Slotted wings)	Eagles, Hawks, Pelicans, vultures, storks	Deep slots between feathers for catching air Mostly rectangular in planform geometry while in flight. Very wide wings and long as well	High aspect ratio Reduced induced drag Reduced wingtip vortices Easy take-off and landing. Can make use of slots to trap air currents over oceans for smooth flight and gliding They're known to be the highest set of fliers	They are not easily maneuverable In practical application where biomimicry is used, they don't provide enough room for the engine wheels to fit in during flight	Cargo planes and small aircraft e.g. Boeing and Airbus
4	Elliptical wings	Flycatcher, passerines, pheasants and partridges etc	Extended feathers to help catch air Narrow and short wings Low aspect ratio	Rapid and easy take off/landing Easy maneuverability Versatile in different situations.	Cannot fly for protracted time periods In actual practice they are not easy to reproduce and manufacture. In practical artificial applications they are very prone to stalling due to their shape and could easily lead to loss of control for pilots	Spitfire war planes used during World War II for bombing

Winglets are vertical attachments at the tip of airplane wings. Engineers drew inspiration from birds such as buzzards, eagles and storks in adapting this design to airplane wings. They are also called vortex arresters. During flight, the feathers on the wing tips of those large birds bend upward until they are almost vertical. This configuration balances maximum lift with minimum wing length. It also improves performance. Engineers have designed airplane wings with a similar shape. Using innovative wind-tunnel testing, they found that if the modified wings were precisely curved at the tip and properly aligned with the airflow, they improved aircraft performance-nowadays by up to 10 percent or more. The reason? Winglets minimize drag by reducing the size of the vortices. Moreover, winglets also create a form of thrust that “counteracts some of the normal drag of the airplane,” says the Encyclopedia of Flight. Winglets thus enable airplanes to fly farther, carry a greater load, have shorter wings-which also facilitates parking—and save fuel. In 2010, for example, airlines “saved 2 billion gallons [7,600 million L] of jet fuel worldwide” and contributed to large reductions in aircraft emissions, says a NASA news release." An illustration is given below in Figure 3.



(a) A plane with winglets

(b) Bird's wingtips curved upwards to reduce drag

Figure 3: Winglets [10]

Delta wings are used on high speed aircraft. This innovation was inspired by the peregrine falcon particularly. The ability of the above mentioned bird to curve its wings backwards and align it close to its body as though it was unconnected in the first instance make it very swift with very low induced drag enabling it to swoop down at unprecedented speeds of up to 322 Km/h. These set of wings are particularly common among fighter jets used by the military for bombing and quick evasion from enemy territories.

The tail feathers of birds also play a crucial role in aiding bird to maintain stability while in flight. Test carried out on a barn owl by researchers in the University of Bristol, UK showed that birds actively use their tail wings to aid stability and also generate lift. Though this is one sided in practical application (planes use their tail wings for stabilization not lift), engineers are optimistic that in time to come certain categories of drones will be able to fully mimic this quality of birds.

The B-2 Bomber designed and utilized by the United States armed forces has a lot of similarities in shape and performance to a stooping peregrine falcon. Its ability to hit marked targets and also easily maneuver from enemy lines is very much akin to a peregrine falcon on the hunt which can achieve a stoop speed of close to 400 Km/hr and also easily lift off and maneuver with its prey at very tight angles and conditions. The bomber is hence is very effective and is able to imitate to a very large extent this aerial predator. These are shown in Figure 4.

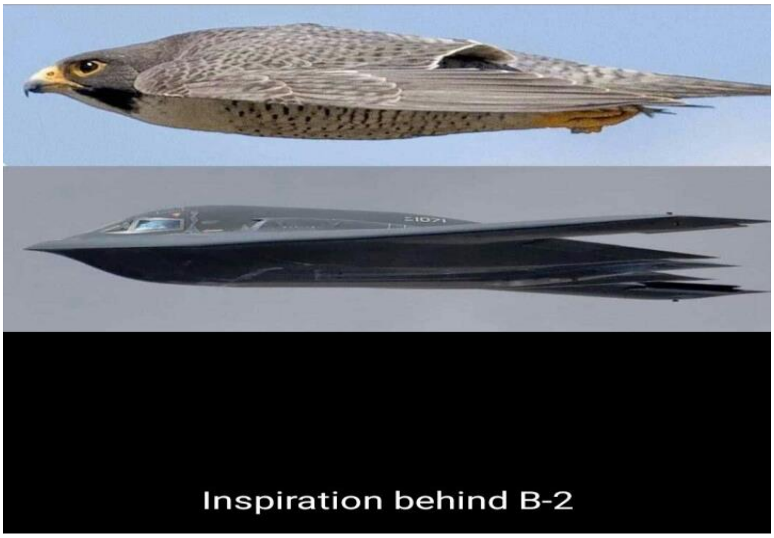


Figure 4: Nature and its imitation; A stooping peregrine falcon and a B-2 Bomber [11]

In addition to being able to hover for protracted time periods mid-air, small birds also have the ability unlike their larger counterparts to immediately jump into flight. Most large birds need to run or fly very close to the ground before generating enough energy to take off into full fledged flight. The reverse however is the case for hummingbirds and other small birds like terns, kestrels, kingfishers among others. Helicopters and particularly drones mimic this quality of such birds and are able to also go into full-fledged flight and sustained hovering without any need of a runway.

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. This innovation therefore is the most perfect artificial representation of a bird currently by engineers and scientists. It is also easier to design when compared to a standard aircraft. This particular design in question will be the focus of our project. An illustration is given below in Figure 5.

Figure 5: Ornithopter- [12]

Another very important factor underlying the ability of birds to cruise at enviable heights and wild speeds comfortably is streamlining. First of all Streamlines are defined as the path taken by particles of fluid under steady flow conditions. It can also be said to be a "path of a fluid flowing steadily and without appreciable turbulence. A body is said to be streamlined if its shape offers the least possible resistance to a current of air, water, or other fluid. The current that a streamlined body breaks simply reunites in its wake, as contrasted with the retarding eddies and turbulence created by the partial vacuum in the wake of a non-streamlined body. The streamline design is typically a long ellipse tapering to a point in the direction of flow; it is illustrated in the cross section of an airplane wing and in the bodies of fishes and birds. Vehicles such as automobiles, aircraft, railroad cars, and boats are designed to provide maximum streamline [13]. On the other hand, "Streamlining, in aerodynamics, is the contouring of an object, such as an aircraft body, to reduce its drag, or resistance to motion through a stream of air [14]. Simply put, it can be defined as the act and process of making a body streamlined or into a streamline shape. In addition, "Streamlining, then, is the contouring of an aircraft or other body in such a way that its turbulent wake is reduced to a minimum. The mechanics of airflow patterns lead to two principles for subsonic streamlining: (1) the forward part of the object should be well rounded, and (2) the body should gradually curve back from the midsection to a tapering rear section. An efficiently streamlined body thus takes on the look of a horizontally inclined teardrop shape. In Houghton and Carpenter's words, "Streamlining is vitally important for reducing form drag [8] Summarily, this is one very essential properties that birds possess; the ability to perfectly streamline their bodies to overcome drag and hence glide effortlessly through the air. An illustration is given in Figure 6.

Figure 6: Streamlined shape of a bird in flight [15]

"There are about 9000 species of birds in nature. Birds show people their excellent flight capabilities and inspired people to develop similar bio-inspired flight systems. The humans' initial exploration of flying began with imitating birds. In each period of the history of human civilization, much effort has been devoted to the invention and design of bird-like aircraft or the improvement of the flapping-wing theory. Especially in the early days of bionic aircraft research, because the key technologies involved in the research of bird-like aircraft are relatively mature, the research of bio-inspired flight systems begin with bird-like flying vehicles. In a recently concluded study by four Chinese engineers documented in the Chinese Journal of Aeronautics, titled: "Review on bio-inspired flight systems and bionic aerodynamics", a brief review of the efforts of engineers in times past is highlighted. The paper also reviewed and discussed the development of Micro Air Vehicles (MAVs) of which this researchers document is subdivided into three smaller categories. "The current MAVs are mainly classified into three categories: Fixed-wing Micro Air Vehicle (FMAV), Rotary-wing Micro Air Vehicle (RMAV) and flapping-wing micro air vehicle (also called biomimetic, BMAV) according to their flight principle and aerodynamic layout. In fact, the flapping-wing micro air vehicle is accompanied by the use of the bionic concept.

They concluded their research/review report thus: "The bio-inspired flight systems represent the most exciting and challenging direction for the development of future flying robots. With the higher requirements of autonomous and intelligent bionic aircraft, the bionic aerodynamics related to the bio-inspired flight systems also faces greater opportunities and challenges.

"The retarding effect of air on a moving object was among the earliest aerodynamic phenomena to be explored. Aristotle wrote about air resistance in the 4th century BC [16]. But lacked the understanding to quantify the resistance he observed. In fact, Aristotle paradoxically suggested that the movement of air around a thrown spear both resisted its motion and propelled it forward[3] "In the 15th century, Leonardo da Vinci published the Codex Leicester, in which he rejected Aristotle's theory and attempted to prove that the only effect of air on a thrown object was to resist its motion [3] and that air resistance was proportional to flow speed, a false conclusion which was supported by Galileo's 17th century observations of pendulum motion decay [16].In addition to his work on drag, da Vinci was the first person to record a number of aerodynamic ideas including correctly describing the circulation of vortices and the continuity principle as applied to channel flow [16].

"The true quadratic dependency of drag on velocity was experimentally proven independently by Edme Mariotte and Christiaan Huygens, both members of the Paris Academy of Sciences, in the late 17th century [3]. Sir Isaac Newton later became the first person to theoretically derive this quadratic dependence of air resistance in the early 18th century, making him one of the first theoretical aerodynamicists. Newton stated that drag was proportional to the dimensions of a body, the density of the fluid, and the square of the air velocity, a relationship which was demonstrated to be correct for low flow speeds, but stood in direct conflict with Galileo's earlier findings. The discrepancy between the work of Newton, Mariotte, and Huygens, and Galileo's earlier work was not resolved until advances in viscous flow theory in the 20th century. Newton also developed a law for the drag force on a flat plate inclined towards the direction of the fluid flow.

[17] in his paper titled aerodynamics of bird flight noted that in very recent history, "Cruising flight has been filmed many times and these films, however interesting they may be, do not answer the most interesting (from the aerodynamics point of view) sequences of bird´s flight like take-off and landing. This has changed in the last decades thanks to high speed cinematography and recently even to video recording using miniaturized cameras placed directly on the bird´s body [17]. Using (where) F for the drag force, ϱ for the density, S for the area of the flat plate, V for the flow velocity, and θ for the angle of attack, "This equation overestimates drag in most cases, and was often used in the 19th century to argue the impossibility of human flight [16] .At low inclination angles, drag depends linearly on the sin of the angle, not quadratically. However, Newton's flat plate drag law yields reasonable drag predictions for supersonic flows or very slender plates at large inclination angles which lead to flow separation. "Air resistance experiments were carried out by investigators throughout the 18th and 19th centuries. Drag theories were developed by Jean le Rond d'Alembert and Lord Rayleigh. (Rayleigh, Equations for fluid flow with friction were developed by Claude-Louis Navier and George Gabriel Stokes. To simulate fluid flow, many experiments involved immersing objects in streams of water or simply dropping them off the top of a tall building. Towards the end of this time period Gustave Eiffel used his Eiffel Tower to assist in the drop testing of flat plates."

"A more precise way to measure resistance is to place an object within an artificial, uniform stream of air where the velocity is known. The first person to experiment in this fashion was Francis Herbert Wenham, who in doing so constructed the first wind tunnel in 1871. Wenham was also a member of the first professional organization dedicated to aeronautics, the Royal Aeronautical Society of the United Kingdom. Objects placed in tunnel models are almost always smaller than in practice, so a method was needed to relate small scale models to their real-life counterparts. This was achieved with the invention of the dimensionless Reynolds number by Osborne Reynolds Reynolds also experimented with laminar to turbulent flow transition.

He continues thus " The wind tunnel tests were aimed at two groups of problems–direct measurement and evaluation of lift and drag from measuring in wakes, and in vivo measurements of the origin of these forces. Wakes behind flying birds can be investigated experimentally in wind tunnels by application of several highly sophisticated experimental methods developed for experiments on airplane models [17]. In the studies of the aerodynamics, he therefore states that "Experiments were carried out using a closed loop, low-turbulence wind tunnel designed for bird flight experiments. Four juvenile thrush nightingales *Luscinia luscinia* L were caught, and after a period of acclimatization they were exposed to daily flight training for more than two months prior to experiments, under conditions that gradually resembled the experiment. Training started with low ambient light conditions, introduction and maintenance of fog particles and occasional bursts of high intensity laser light [17].

However, around the year 2015, Dvorak highlights that "Recently, a special wind tunnel has been designed - the so called Aerodynamic force platform (AFP), to measure directly the forces on bird wing during the bird flight. The AFP is a box instrumented with load cells enclosing the object (the bird) that generates the unsteady fluid force. According to Newton's 3rd law applied to a fluid, the unsteady net fluid force needs to be supported by an equal and opposite net force that acts on the control volume boundary [17]. He then adds that "The aerodynamic forces on the bird wing during takeoff and landing were successfully measured in vivo by pressure transducers and accelerometers built in directly in the wing [17]. Finally, he concludes with the following remark "The sole issue of generating lift and thrust by moving wings may even motivate us to reassess our knowledge on the same issue from the classical fixed wing aerodynamics [17].

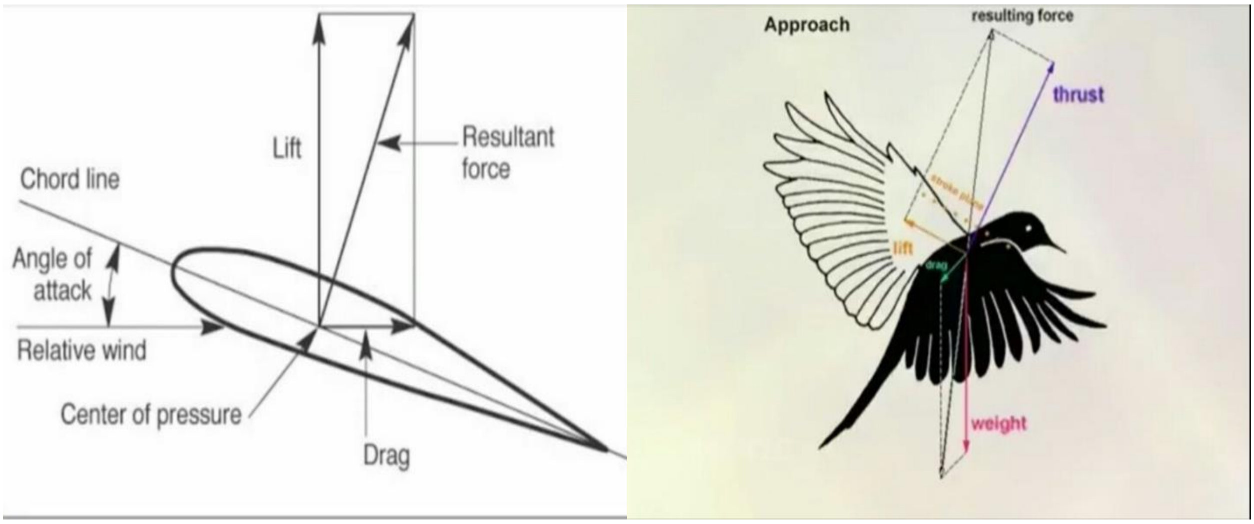
Another writer cum researcher Cone Jr did a lot of manual-mathematical analysis without the aid of special computers, systems or softwares but mostly from the physics and mathematical point of view. In his published work: The Aerodynamics of Flapping Bird Flight published in October of 1968 noted that "The wing forms and flight patterns of birds cover an enormous range of variations, and these variations in turn reflect the specific adaptation of the bird to a particular system of environmental factors. As particular analysis will clearly show, the wing is not always designed for the highest aerodynamic efficiency in distance travel; accommodation of other factors may be much more influential in deciding wing form [18]. At this point in history, many simulation systems were not yet available for such aerodynamic research. The author therefore depended mostly on video clips and photographs of birds in flight. He nevertheless did a very good analytical job on bird's flight at least from the mathematical point of view.

It is also worthy of note that the renowned Airbus corporation not too long ago, precisely in 2019 made some new innovations with respect to their aircraft though this discovery has not been fully implemented yet. At the above stated time it was still in the testing and simulation phase by its engineers. Extra little wing attachments called "flapping wingtips" similar in geometry to winglets were attached to the main wing at its tips. They are however not fixed like winglets but can be adjusted just like flaps and slats and can be allowed to flex while in flight. The wing tips are semi elastic in nature and are produced from composite materials. Albatross-1 is the name of the demonstrator (prototype). According to the engineers, they are designed to mimic the aerodynamic quality of birds and are able to improve flight efficiency. In the chief engineer's words, "Semi-aero elastic hinged wing-tips enable an aircraft to "surf" through wind gusts without transferring 'the bending loads (i.e. external load that produces bending stresses within a body) to the main wing. This means we require less material such as carbon-fiber-reinforced polymers to make the wing strong enough to withstand the gust loads, thus reducing the weight of the aircraft. The corporation believes that this innovation has the potential to reduce a significant amount of fuel burn and carbon dioxide emissions which will also help in environmental conservation and preservation amidst prevalent climate change concerns. It would also allow aircraft to have far greater wingspans without any significant increase in overall weight. In addition, the team leader of the Airbus Hinge project; Tom Wilson explains that "Lift-induced drag accounts for about 40% of a large aircraft's drag. But this figure falls as the wing span increases. The semi-aeroelastic hinged wingtips' span could potentially be increased beyond 50 meters without increasing wing weight.

In light of the already existing literature, it has been discovered that no research has been carried out yet on the possibility of adding feet and even retractable wings (as is evident in actual birds) to ornithopters as this is our application of interest while for normal conventional airplanes, research has likewise not been carried out on modifying its outlook to maybe multiple wings or actual flapping of wings to initiate take-off and landing.

2.0 Materials and Methods

A number of forces are in action during the activity and process of Bird flight. These principles turned out to be the underlying factors considered when building artificial flight machines. Four forces are at work to enable a bird fly. These forces are illustrated in Figure 7.



(a) Analytics of a wing. (b) Analysis of forces on a flying bird

Figure 7: Forces at work during Flight [6]

2.1 Analysis and Design

In the light of the already existing aerodynamic theories and our initially proposed design, we carried out an understudy and analysis of some already existing aircraft designs in relation to the birds of interest with the aim of proving firsthand the already established conclusions on their behavior. Due to lack of facilities and equipment relevant to this topic in this part of the world, new discoveries and initially planned modifications could not be made. Also, we eventually designed a biomimetic aircraft known as an ornithopter in the light of the already stated limitations on the scope of this work and have simulated its performance and behavior using the Solidworks CAD software and ANSYS. The final design (skeletal frame) and product looks thus as shown in Figure 8.

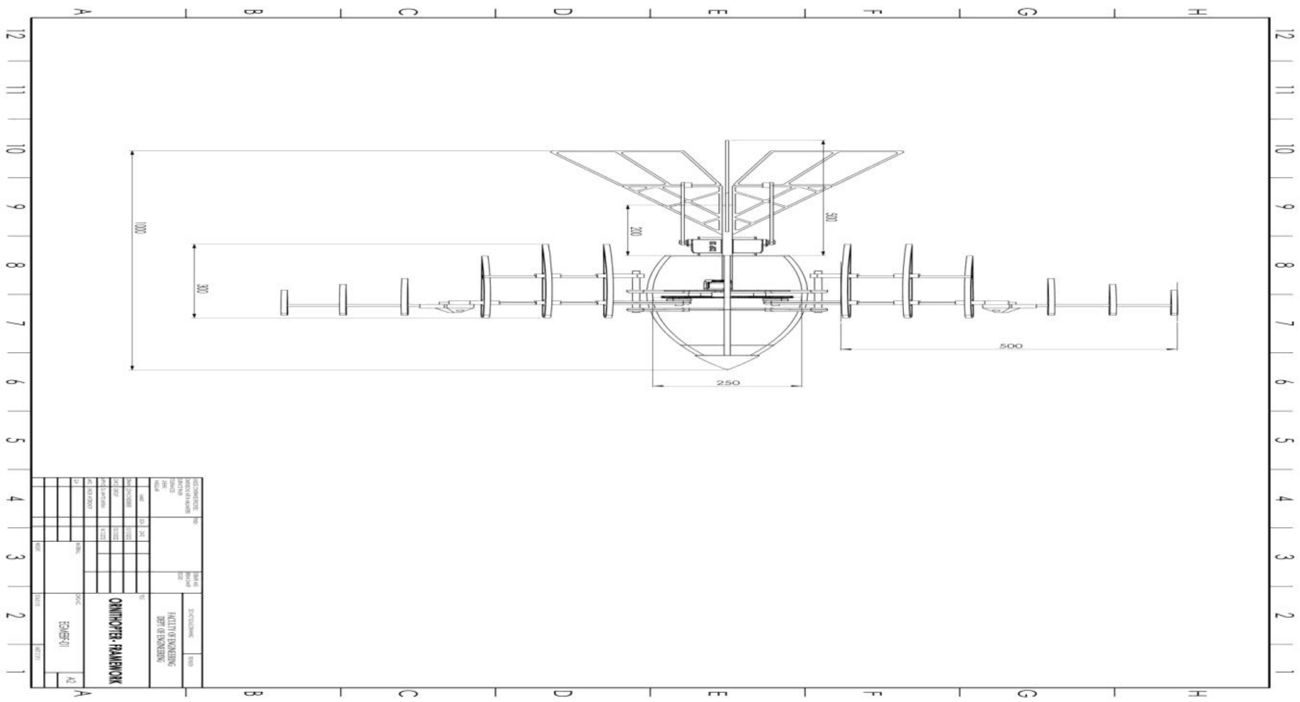


Fig 3.2: Top view (plan) of the Design's Framework

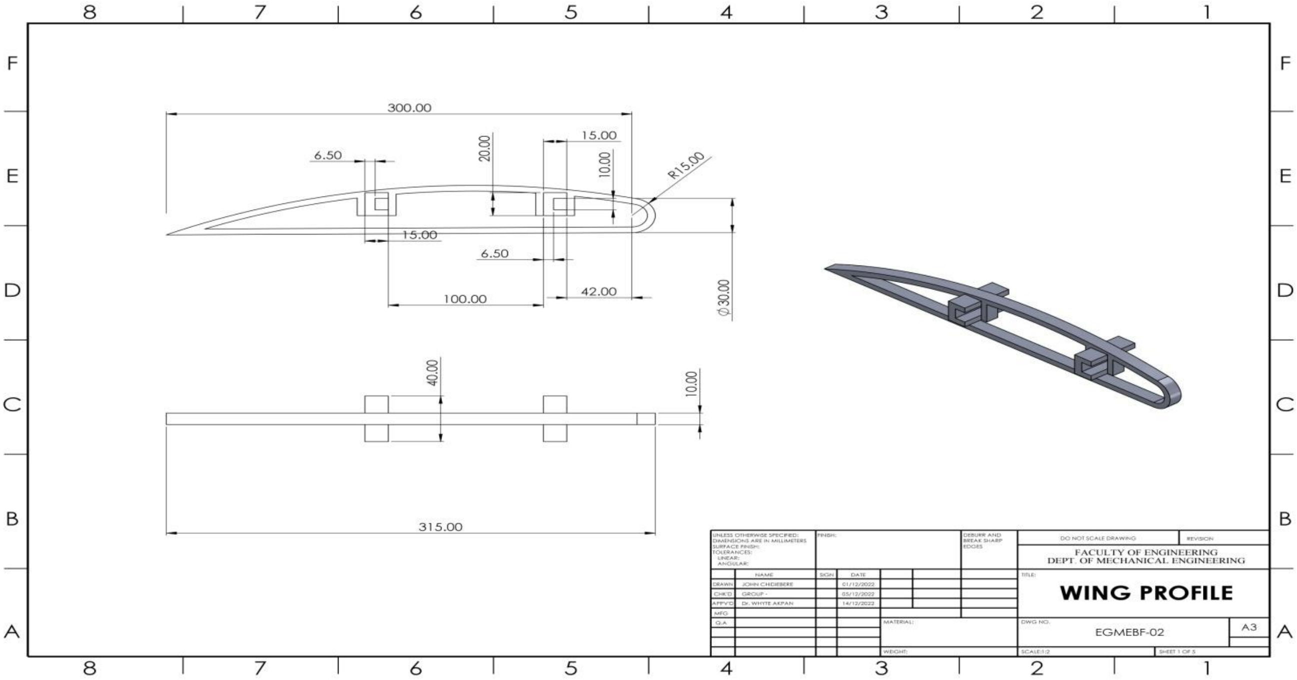


Fig 9: Wing Profile used for design

Figure 9 shows the wing profile used for the design.

2.2 The Working Principle and Mechanism of an Ornithopter

An ornithopter is the best artificial representation of a bird. It can a robotic bird. It is a composite product of mechanical, electrical and computer engineering in some cases. It works on the principle of flapping flight. Conventionally and traditionally, it is powered by lithium dry cell batteries and its wings are driven by a set of gears or gear mechanism. Light weight materials are used in its production from the inner framework to the outer body. This will enable it to achieve heavier than air flight as heavy components will only frustrate the flight endeavor**.** An ornithopter operates on the principle of flapping flight as continuous flapping of the wings is needed for this machine to stay airborne. Thus far the bird is manually aided to attain initial take off as there is currently no discovered way for it to take off on its own. Also, our design was limited to the mechanical aspects of the machine which include the gears, the aerodynamics and its structure.

2.3 Design Requirements, Criteria and Calculation.

The design requirements are presented in Table 2.

Table 2: Design Requirements

S/N	Parameter	Unit/Dimension/Specification	S/N	Parameter	Unit/Dimension/ Specification
1	Wing span	800mm	6	Control	Remote Controlled(RC) type
2	Chord length	300mm	7	Aspect ratio	4

3	Craft length	1000mm	8	Flapping frequency	1.5 to 2Hz
4	Average weight	1.5Kg	9	Power source	Battery (Lithium-ion)
5	Motor	Brushless DC motor (BLDC)	10	Drive mechanism	Gears

Taper ratio is given by:

$$T=\frac{C_T}{C_R}$$ Equation 1

where C_T is the chord at the tip and C_R is the chord at the root

Therefore, the taper ratio using the above Equation is:

$$\frac{15}{30}=0.5$$

To determine the velocity of the craft, using the standard lift coefficient (C_L) of the NACA 7412 aerofoil which is given as 0.1557 and using Equation 2.

$$V=\sqrt{\frac{F_L}{0.5\varrho C_L A}}$$ Equation 2

From analysis and standard conventions, the lift force, F_L is equal to the weight, W. And density, ρ is equal to 1.2 and planform area, A as S calculated is 0.27m^2. Therefore, substituting values gives, V as5.63m/s
Calculating for the thrust force F_T which is equal to the drag can be done with equation 2.5 by making F_T subject of the formula. Therefore, F_T is given by the formula Equation 3.

$$F_T = 0.5\ C_D V^2 A\varrho$$ Equation 3

Substituting values, where C_D for the used NACA 7412 airfoil is 1.1667, thrust force F_T equals to 5.99N.
Also to find the gear reduction ratio, Equation 4 below is used.

$$\text{Gear reduction ratio} = \frac{\textit{Number of teeth on reciprocating gear}}{\textit{Number of teeth on motor gear}}$$ Equation 4

The reduction ratio$=\frac{72}{18}= 4$

Table 3 shows the gear train data.

Table 3: Gear Train Data

S/N	Gear	Pitch Diameter	Spindle Diameter	Module	Face width	Number of Teeth
1	Motor gear	20mm	5mm	1.11	8mm	18
2	Reciprocating gear right	72mm	-	1	8mm	72
3	Reciprocating gear left	72mm	-	1	8mm	72

Wing loading is calculated as weight (in kilograms) divided by the wing area. It is thus;

$$1.5/S$$

where S = b × c (from Equation 4)

But since chord length varies across the wing cross section, the mean average chord (MAC) will be used.

Therefore, MAC and calculated using Equation 5.

$$\frac{C_R + C_T}{2} \qquad \text{Equation 5}$$

where C_R and C_T are the chord lengths at the root and tip of the body respectively.

Substituting the values gives

$$\text{MAC} = \frac{15+\ 30}{2} = 225\text{mm}(22.5\text{cm})$$

Therefore, wing area, $S = 1200 \times 225 = 270{,}000\text{mm}^2$

Wing loading is therefore equal to $\frac{1.5}{0.27} = 5.56\text{Kg/m}^2$

The aspect ratio is given in Equation 6

$$AR = \frac{b}{c} = \frac{b^2}{S} \qquad \text{Equation 6}$$

where b is the wingspan, c is the standard mean chord or chord length, S is the surface area of the wing is 1.2m and 0.3m in order to achieve the desired aspect ratio of 4

Also calculating for the flapping frequency of the ornithopter, using the Lippisch formula in Equation 7.

$$f = \sqrt{\frac{W}{\left(\frac{\rho}{2}\right) \times b^3}} \qquad \text{Equation 7}$$

where W is the weight of the craft, ϱ is the air density (approximately 1.20kg/m^3 at standard temperature and pressure), b is the wing span (1.2m) and f is the frequency. Substituting values, f is equal to 1.20Hz. This calculated value therefore corresponds to the initial design requirement.

Also, to power the gear train for the wings, a 900Kv Brushless motor was found to be suitable to be powered by a 4 to 5 cell Lithium-polymer battery, with a working current of 35-60 Amps and a peak current of 80 Amps. It weighs 250 grams and has the initially shaft diameter of 5mm which is optimally suited to our reducing gear design.

Finally, the tail is C-Configuration tail design with a vertical rudder and horizontal elevators. This was chosen due to the fact that the rudder provides directional stability, high level manoeuvrability of the tail as a whole, permits a large range of flight speeds. Also, low speeds are possible due to the extremely high angles of attack the ornithopter can reach with this type of tail.

3.0 Materials Selection

Materials selection is given in Table 4 in the case of a possible production.

Table 4: Parts and Material Selection

S/N	Part	Material	Justification
1	Gears	Carbon fibre	High tensile strength, stiffness and rigidity
2	Outer covering	Polyurethane Foam	Durability, corrosion/abrasion resistant, water/airtight, cost effective
3	Inner Framework/Wing spars	Carbon Fibre	Light weight, high stiffness and rigidity.

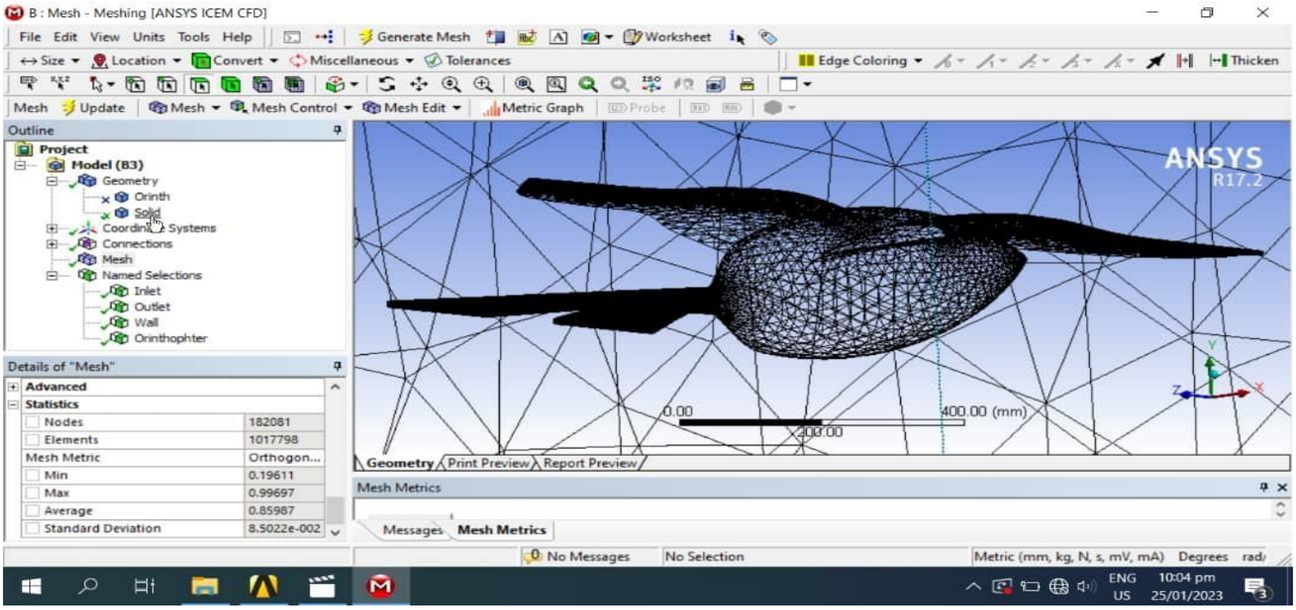
4.0 Results and Discussion

The velocity and pressure of the ornithopter was analyzed using the ANSYS Fluent software with simple discretization technique. The fluid was set to air with inlet velocity specified as an X- component with magnitude of 5m/s. Oversight considerations are made for wall motion and shear boundary conditions. This analysis was carried out under steady-state transient conditions.

4.1 Creating Quality Mesh

The model which was created with Solidworks was imported to Ansys ICEM CFD and edges were added for easy mesh manipulation. The generated mesh was refined by adding face and edge sizing. The relevance centre was changed from coarse to fine, the maximum mesh size set to 45 mm. The edge sizing was applied around the ornithopter wings and tail boundaries with an average of 92 edges selected and 50 divisions used. This amounted to a total of 182081 nodes and 1017798 elements as depicted in Figure 4.1. The process is repeated for the remaining bird flight configurations.

Since five different mesh configurations were required for analysis in fluent, five independent mesh with an orthogonal mesh metric was connected to the Fluent on the ANSYS workbench using links. The generated mesh for the ornithopter for velocity magnitude and pressure distribution is as shown in Figure 10.



Details of "Mesh"

Advanced	
Statistics	
Nodes	182081
Elements	1017798
Mesh Metric	Orthogon...
Min	0.19611
Max	0.99697
Average	0.85987
Standard Deviation	8.5022e-002

Figure 10: Mesh refinement for the bird flight analysis

4.2 Pressure and Velocity Magnitude of the Bird Flight

Using the CFD post processing module in ANSYS, the pressure distribution is determined using the coefficient of pressure. At the leading edge of the wing of the ornithopter, there is a decrease in pressure (-2.71e+01) far below as expected of fluids being subjected to airflow. As it acceleratesagainst the wind, there is an increase in velocity. The Y component of the bird flight has a velocityof 0.00986m/s, the X component of velocity is 8.98m/s. The pressure and velocity magnitude results are shown in Figure 11 and Figure 12 respectively.

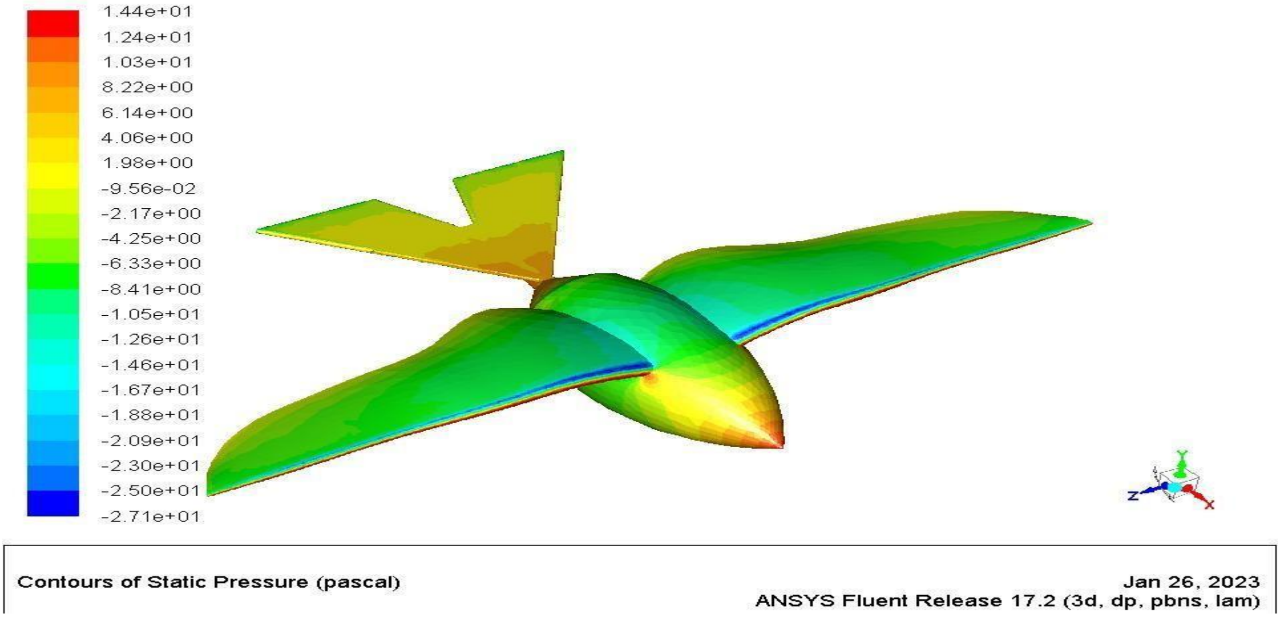


Figure 11: **Pressure distribution of the ornithopter**

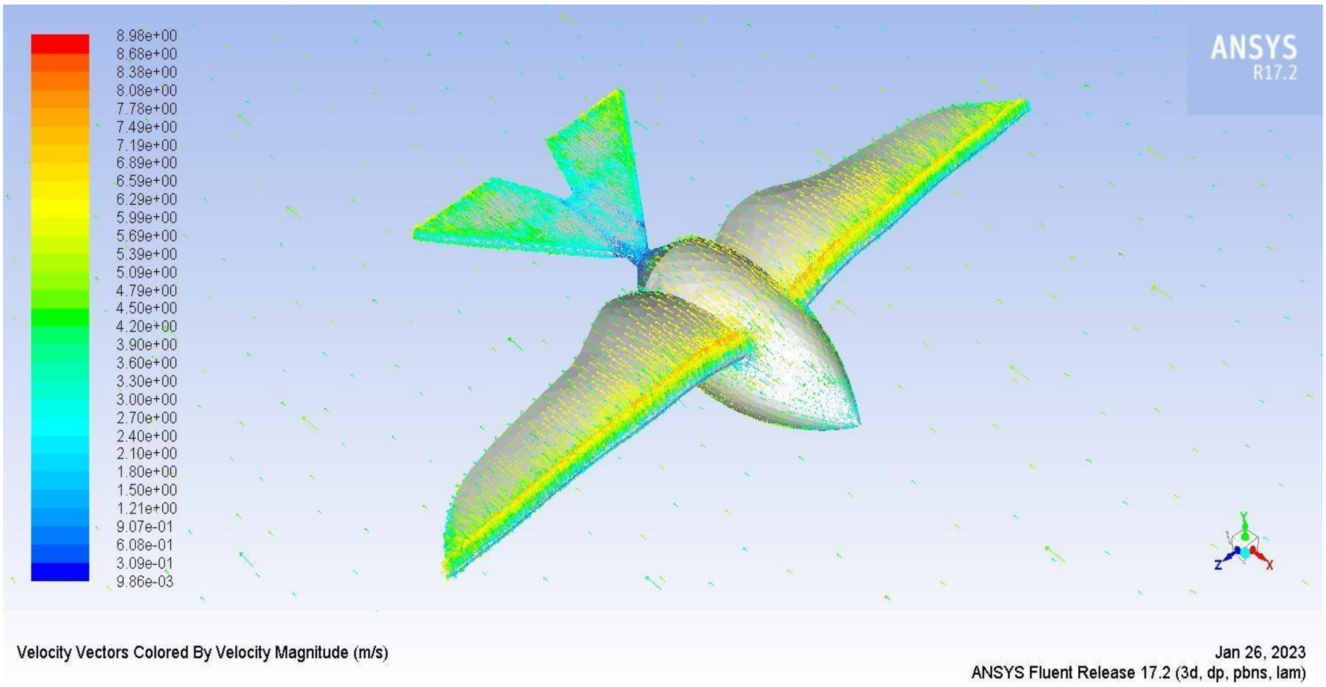


Figure 12: Velocity vectors and magnitude of the ornithopter

Figure 13 is the model of the completed design using the SolidWorks modeling application

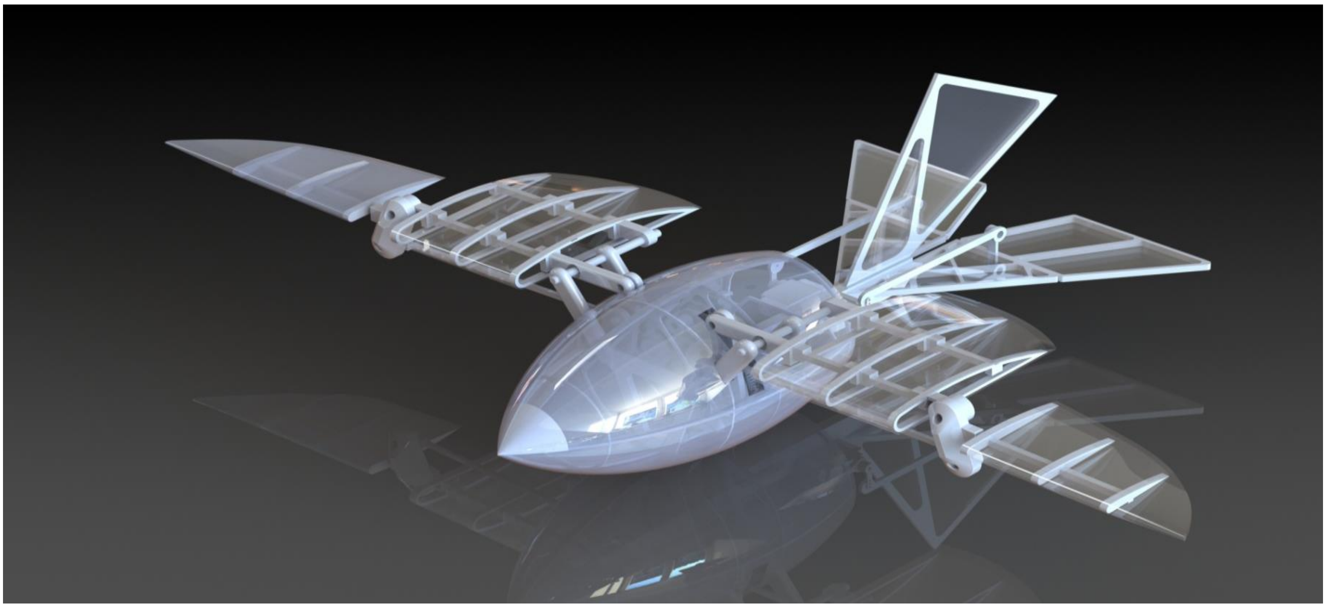


Figure 13: A Three Dimensional View of the Completed Design

4.3 Direction of Measurement of Lift and Drag Coefficient

The lift and drag coefficient as well as the pressure and velocity distribution for the ornithopter with respect to the different altitudes can be determined. These data are presented in Table 5.

Table 5: Coefficient of Lift to Drag

Margin above sea level in metres (m)	Coefficient of Lift (C_L)	Coefficient of Drag (C_D)
100	0.0000	0.0040
200	0.0050	0.0050
300	0.0100	0.0060
400	0.0150	0.0070
500	0.0200	0.0080
600	0.0250	0.0090
700	0.0300	0.0100
800	0.0350	0.0110
900	0.0400	0.0120
1000	0.0450	0.0130

4.4 Discussion

Table 5 above presents the lift and drag coefficients of the ornithopter. The higher the flight above sea level the greater the coefficient of lift. This is due to the obvious fact that air pressure/resistance reduces the higher the altitude. It will take a lot of flapping energy to get the biomimetic aircraft off the ground at sea level and this is a normal phenomenon common to all aircraft. Greater thrust therefore and gear speed will be required at this point as opposed to when it has already attained flight. From the initial specifications and proposed design, little disparities were encountered but also duly fixed. Note worthy is the fact that these results presented above via the simulation was carried out and obtained on a predominantly steady state interface analogous to gliding flight motion of birds. The pressure distribution pattern shown in Figure 11 highlights the tip as the region of highest pressure and this is very much anticipated since the nose of the craft will be first to come in contact with fiery busts of wind and also due to its small surface area. The pressure distribution was between $-2.71x10^1$ Pascal to $1.24x10^1$ Pascal and the velocity $9.86x10^{-3}$ m/s to $8.98m/s$ .Parameters like flight duration could not be readily ascertained as all the work was done on software in line with the earlier stated scope and limitations of this research. Also, in the event of actual production, the services of an electrical and computer engineer are deemed necessary as they will be better placed to handle both programming and control aspects of the design.

5.0 Conclusion

Optimization of existing flight modes -in biomimetic fields, methods and vehicles was achieved, thus increasing efficiency and reducing energy and power losses. The various factors which enable birds to be so efficient in flight were identified and applied to real world and actual flight machines in order to enhance efficiency and optimum operation. In the aftermath of this research work, simulation and information and data derived from this activity is expected to be useful mostly in the aviation sector. That similar project (i.e., with regards to aerodynamics) be undertaken on other flying species like insects, bats and even aquatic animals as overall principles of locomotion are quite similar the only difference being a change in fluid media water

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