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Evolutionary and Hereditary Traits of an Albatross and its Aerodynamic Optimality

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Abstract. The aerodynamic efficiency of the albatross has always fascinated researchers and the designing of drones mimicking the albatross's aerodynamic traits have been a major area of interest for the aerospace industry. This review sheds light on the traits behind an albatross's aerodynamic efficiency such as dynamic soaring, bell shaped lift distribution and provides insights into its hereditary posed encodings and evolutions. The soaring techniques have been introduced and discussed along with the albatross's morphology and structure which is responsible for its efficiency. In addition, the albatross's navigational and foraging strategies are briefly discussed to provide a better understanding of the effects of atmospheric conditions on the albatross's flight characteristics and the limitations.

Keywords: Aerodynamics, albatross, bio mimetic, dynamic soaring, bell shaped lift distribution.

1. Introduction

Wings of different species of birds have evolved in order to adapt to different niches. Lift generation is due to the pressure difference caused by fast flowing air on dorsal side of the wing than on the ventral side. Flapping flight is comparatively more complex than other types of lift generation. A lot of energy is required for take-off and landing. Drags acting on a bird during its flight are skin friction drag, form drag and induced drag. Birds have undergone evolutions to counter these drags and in order to adapt. This is different for different bird species. The albatross has pointed wing tips and a wing with high aspect ratio; high lift to drag ratio and high wing loading [1].

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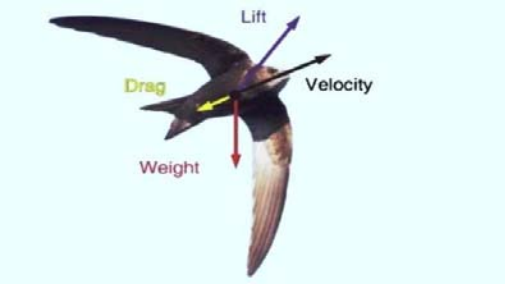


Figure 1: Forces acting on a bird [16]



Figure 2: The Albatross [12]

Albatrosses are large birds and they mostly utilize soaring flight modes and their habitat is mostly nearby the surroundings of oceans where the wind velocity is generally high. Unlike birds, structural changes can be made for aircrafts. Birds already have the ability to modify their muscles, feathers etc. During dynamic soaring, one would not observe deflections on wingtips of an albatross despite it flying at around 3Gs. This clearly indicates that very small amounts of load is acting on the wingtips of the albatross and unlike a wing with an elliptical lift distribution, the shedding of wingtip vortices is gradual and not abrupt. This property is exhibited by a wing with a bell shaped lift distribution.

2. Review of Literature

2.1. Bell shaped lift distribution, proverse yaw and wing tip vortices

Prandtl, after various attempts, came to the conclusion in 1921 that a distribution of lift over the span according to a half ellipse will exhibit the desired result. In a wing with an elliptical Plan form, the up wash and downwash is constant with same lift co-efficient at every point from wing tip to root. When the angle of attack is altered, the up wash and downwash too get altered and the summation comes out to be a total downwash which is constant from wing tip to wing root.

Elliptical lift distribution yield optimum results for some special cases involving prescribed span and gross weight. Elliptical lift distribution exhibits minimized induced drag on a straight wing with prescribed wingspan and lift. Various assumptions were taken into account during the formulation. On further research, a more efficient lift distribution was obtained which was shaped like a bell with gradual tapering of lift values to zero at wingtips. This bell-shaped lift distribution proved to be more efficient than the elliptical lift distribution [2].

Ludwig Prandtl in 1933 gave a minimum induced drag solution for a wing of constrained mass [3].

- 11% less Di, 22% greater wing span than ELD
- Up wash at wingtips
- Proverse Yaw
- Tailless flight

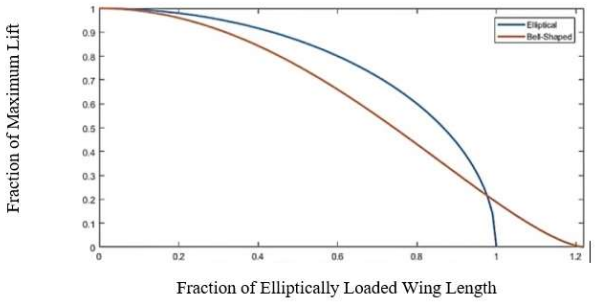


Figure 3: Elliptical and Bell Shaped Lift Distributions [3]

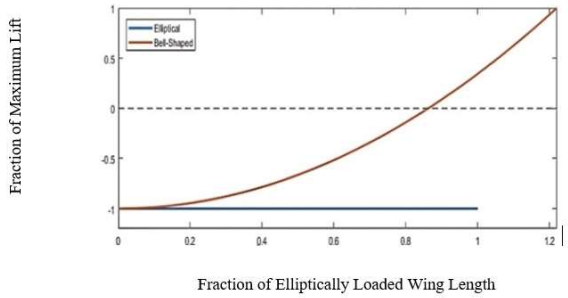


Figure 4: Elliptical and Bell Shaped Lift Distributions [3]

PRANDTL-D
Preliminary Research Aerodynamic Design to Lower Drag

Features of BSLD-

- Magnitude and Direction of downwash at the trailing edge is a function of span wise position.
- Unlike the Elliptical Span load where the downwash is constant, in Bell Shaped span load the downwash is characterized by a quadratic function with maximum downwash at the root.
- Relative wind at the wingtips is angled upwards.
- Induced thrust is produced at wingtips. Even if there is no vertical stabilizer, if yawing moment produced by the induced thrust is large, the aircraft is capable of undergoing a coordinated turn. Induced thrust is produced at the wingtips due to resulting up wash at the wings.
- Ludwig Prandtl derived the Bell shaped lift distribution and tested a flight as a proof of this concept [4].

Comparing wings-

- Smallest wingspan- rectangular wing
- Highest drag- trapezoidal and ELD wings
- Most efficient- BSLD

The reason for high induced drag on a rectangular wing is because of low aspect ratio. Also they must maintain a high angle of attack at low speeds as at these speeds, lift is generated by vortices. They are comparatively easier to manufacture, e.g., Piper PA38. In a trapezoidal wing the leading edge is swept backwards and the trailing edge is swept forwards. It is efficient for supersonic flights but due to their high wing loading, maneuverability is comparatively low e.g., Lockheed Martin F-22 Raptor. Flying wings lack tails but they provide an increased efficiency. However to achieve this efficiency, certain measures have to be taken. These include adding a swept angle. But addition of a swept angle will in turn increase the induced drag. Hence, despite providing pitch and yaw stability, the net performance of the aircraft will ultimately get reduced. But the Bell Shaped Lift Distribution has the characteristic of proverse yaw, which will have the combined advantages of a rolling control and elimination of this sweep angle [5]. In an elliptical lift distribution, the up wash and the downwash is constant with the lift coefficient at every point from tip to root. On increasing the angle of attack, the up wash and the downwash will get altered and the resulting summation will give us a total downwash which in turn is constant along the span. But a different trend is observed in case of Bell Shaped Lift Distribution where it consists of both up wash and downwash. A transition is observed from downwash to up wash and this is where the vortices are shed. This means that unlike an Elliptical Lift Distribution, in Bell Shaped Lift Distribution the vortices are shed at around 70-80% of the span. This is precisely the reason why we do not observe the deflection of feathers on the wingtips of an albatross during dynamic soaring even at 3Gs.

In an ELD wing, there exists uniform downwash along the wing's trailing edge, and a sharp discontinuity of up wash and downwash at the wings results in strong, tightly rolled vortices being formed at the wingtips. But in BSLD, a transition of downwash is observed with strong downwash at the roots and up wash at the tips. The net force vector is a function of span for BSLD, i.e., the net force varies span wise. Inboard, force vector is tiled away from relative wind and the parallel component produces the induced drag. Progressing outboard the parallel component reduces in magnitude till it becomes tilted into the relative wind. This generally occurs past b/2 at around 0.704 of span. This is the Induced thrust which is negative of Induced Drag. Sum total is net drag but locally at around 0.296 of span, Induced Thrust is produced [6].

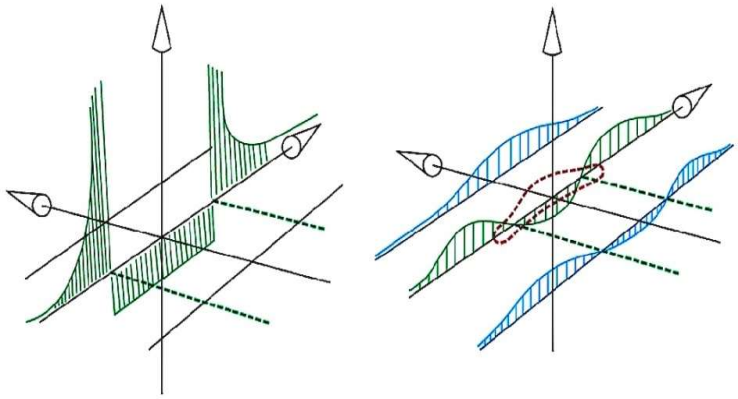


Figure 5: Up wash and Downwash of Elliptical and Bell Span loads of Ludwig Prandtl [6]

When deflection of control surface is done near the wingtips, increasing the lift near one wingtip will result in the desired bank angle. Increasing the lift on one wingtip will further increase the Induced thrust, hence the raised wing will create more thrust than the lowered wing resulting in bank and yaw in the direction of turn. In this manner, proverse yaw facilitates coordinated flight without a tail, rudder or other drag devices. To understand the proverse yaw attribute of bell shaped lift distribution, one must know what adverse yaw is. Adverse Yaw is the natural tendency of an aircraft to yaw opposite to the direction it rolls. During rolling, we increase lift on one aileron and decrease the lift on the other aileron. The one producing more lift undergoes slipping or produces induced drag. This causes the aileron producing more lift to yaw opposite to the roll. This can be countered by using the rudder. Another measure to counter adverse yaw is installation of Friese ailerons or differential ailerons. In this type of ailerons, the one going up goes farther than the one going down. Proverse yaw is essential in countering adverse yaw. Proverse Yaw is the tendency of an aircraft to yaw in the direction of roll. Induced Drag can be reduced by increasing the Aspect Ratio, using washout, addition of a span wise twist or by changing the airfoil section near the wingtips.

Aircraft having twist geometries have increased proverse yaw control power as the vortex shed lines shift towards the root. Therefore a larger up wash area is observed which indicates more proverse yaw control power (aircrafts having twist have increased proverse yaw control power with no increase in roll authority). Maximum amount of proverse yaw control power is observed when outboard wing control surface encompasses the entire up wash region. There might be some conflicts. Even local downwash influences proverse yaw control. At the wingtips, imbalance of pressure which is responsible for lift generation causes high pressure air from lower side to curl up to the upper side of low pressure, thus creating wingtip vortices [7]. The vortex layer can be divided into three regions based on a relation to turbulent boundary layer- the vortex core (inner) region, logarithmic region, defect low region. At zero angle of attack, tip vortices are negligible as lift generation and imbalance of pressure is comparatively very low. Installation of a winglet will provide a significant decrease of these tip vortices both in terms of their size and their magnitude. A winglet reshapes the wake and tip vortices. The maximum vortices inside the vortex core will in turn get reduced [8]. After comparing

the albatross wing with other geometric shapes and then with other migratory birds, it was found that the albatross wing shapes yielded a better lift to drag ratio [9].

2.2. Dynamic Soaring Strategy

The wandering albatross spends a majority of its lifespan in air, whilst traveling over 900kms in a day. They do this by gliding over an ocean using a mechanism called dynamic soaring [10]. Albatrosses perform upwind dynamic soaring. Flying crosswind albatrosses gain airspeed which is in turn balanced by the drag. They generally soar upwind at a faster speed than the wind [11]. Dynamic soaring is a gliding flight strategy which is efficient and cheap energetically. If we consider a wandering albatross, while air-borne it hardly flaps its wings and it does this so efficiently that it can spend weeks above the sea water without having to return to land. Wind speed keeps varying above the sea surface, being almost zero near the water surface. The reason is that friction increases as we move closer to the water surface. The speed of wind increases as we move upwards or farther away from the surface [12].

There are four phases to this cycle of dynamic soaring-

- Climb into the wind or windward climb
- Curve to leeward
- Leeward descent
- A reverse turn close to the flanks of water after which it climbs into the wind again to initiate the cycle from the starting phase.

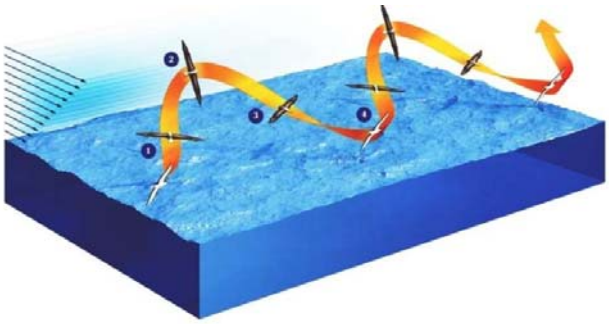


Figure 6: Dynamic Soaring Cycle [12]

The energy keeps varying during these phases with decrease in energy when the albatross is close to the water surface and increase in energy as it climbs into the wind. The wind lift poses as an outboard propulsion engine in order to propel the bird and overcome wind drag. Since the energy gets renewed by the wind as it moves higher, this cycle is almost endless. This means that the albatross can stay air-borne for weeks without the need to flap its wings or having the need to return to land. It engages in a neutral net energy cycle. Albatross inspired UAVs with the ability to perform dynamic soaring can have higher endurance and range, and they can travel farther and longer with lesser amount of fuel intake.

A boundary layer phenomenon is observed above the water surface where the wind layer closest to the water consists of high friction and hence the wind speed gets decreased down to virtually zero. This layer slows the wind speed of the layers above it. This effect can be observed to about 10-20m approximately. This is also called as shear wind field. The albatross extracts energy from this region. The cycle being neutral net energy cycle exhibits no change in total energy at the beginning and at the end of the cycle. Waves, tides or turbulences have little or no effect on the albatross's flight. Highest amount of energy is extracted from the wind during the upper turn. Albatrosses can manipulate the lift distribution with the help of the local shear wind and use this as a propelling unit, more like an outboard engine. This propulsive force is enough to overcome the wind drag in all the four phases. Also a braking phenomenon is observed as it dives closer to the flanks of water in order to initiate the

windward climb. They basically keep flying for free as long as this pattern keeps repeating. During winds of low intensity, they sit and wait on the waters till they encounter an appropriate wind speed. When the albatross changes its direction from windward to leeward in the region of upper altitude, it represents the upper curve of the cycle of dynamic soaring. The upper curve is the region of energy gain, which is the region from which energy is extracted by the albatross continuously from the shear wind. As per gust theory, pulses of energy can be extracted from a separated air flow region which occurs at a low level but on a flat land a region of separated air flow cannot occur; hence energy cannot be extracted in the form of pulses. Instead, energy gain is smooth and continuous in nature and occurs in the upper curve of the cycle of dynamic soaring. While flying over a flat land, the energy extracted for dynamic soaring is primarily from the horizontal wind. For dynamic soaring cycles over flanks of water, wave lift and wave soaring can be considered a primary source of energy extraction. This means instead of horizontal wind, the source of energy gain could be the rising air currents which further imply that the bird would be flying close to the surface of water where the altitude and speed variations are more or less constant. But this is not the case, as energy gain occurs in the upper curve of the cycle of dynamic soaring where air currents and their effects can be considered null. Hence, wave lift and wave soaring have no role in the energy extraction process [13]. When the bird is close to the flanks of water, it decreases the induced drag using aerodynamic ground effect. This is primarily for drag reduction and is unlikely to play any significant role in energy extraction. Gust theory basically deals with discontinuities in wind flow and using gust soaring, albatrosses cover long distances without flapping [14].

2.3. Other Types of Soaring: Thermal Soaring

Though a complex phenomenon, thermal soaring can be defined as a type of soaring wherein the soaring bird flies through columns of warm air currents rising from the ground in a continuous manner. The magnitude at which the bird is descending is of a lower magnitude than that of the rising warm air columns; hence the bird is able to ascend to higher altitudes. This type of soaring can be seen in vultures. Vultures often perform a series of circles while gaining altitude slowly and steadily. It then banks at an angle towards the inner part of the circle. Once the required altitude is gained, it would glide away in a straight path whose length would vary [15]. During this thermal soaring flight mode, birds utilize convection current or thermals for energy extraction without the need for any additional source of power like flapping. When the land gets heated due to solar radiation, nearby air columns rise and form localized parts in the atmosphere temporarily. The birds, as mentioned earlier, use cycling maneuver around thermals to attain the required height and then perform the soaring mode of flight till it reaches another thermal [16].

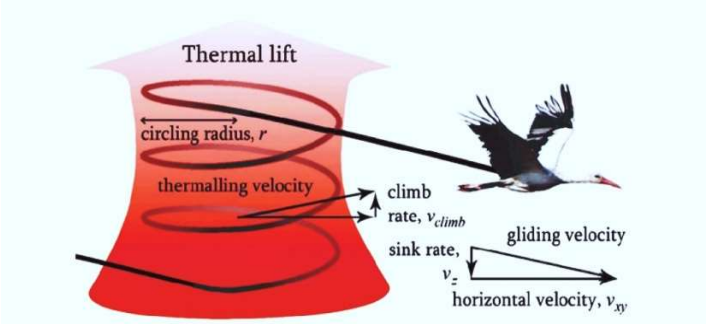


Figure 7: Thermal Soaring [16]

2.4. Evolutionary Colourization of Wings and its Subsequent Effects

Evolutionary colours of the wings of thermal birds like that of an albatross have proved to be an effective factor contributing to the long endurance of migratory birds. The temperature differences between the upper and lower surfaces facilitate a long endurance by aiding in drag reduction. Thermal

analysis done on the boundary layer has been an area of research from the past couple of years. This can be applied to modern drones as well [17].

Flight modes in birds is basically of two types-

- Unpowered- consists of gliding and soaring.
- Powered- consists of hovering and flapping.

During a gliding phase birds do not achieve generation of lift via wing flapping; instead they exhibit conversion of gravitational potential energy into kinetic energy. They produce the required lift by stretching out their wings. In this mode of flight, generation of thrust is not exhibited. Birds like vultures, albatrosses and pelicans use this method due to their large wing which provides a high lift to drag ratio. In a soaring phase, birds use energy from the atmospheric motions and not gravity. Types of soaring include thermal, dynamic and slope soaring. Birds use energy from the wind for dynamic soaring and from convection currents for thermal soaring. Birds use primary and secondary feathers for various purposes like regulation of body temperature, attracting mates and flying. Different colors affect the birds' flight features in different ways. Weak feathers generally exhibit no pigmentation. Black feathers on the wingtips act as agents of strength enhancement. Wings of an albatross are long and slender and are characterized by high aspect ratio and high wing loading. Irrespective of the weather, the upper surface, that is generally black, causes drag reduction. This could be utilized to manufacture bio-inspired UAVs having high endurance. Due to higher solar irradiation during summers, higher values of drag reduction are observed. Darker wings are more efficient with higher endurance. Heat absorption by wings reduces drag during the birds' unpowered modes of flight [18]. In a wandering albatross, the upper surface of wings is black and the lower surface is white. The heat absorption rates of both surfaces vary. Black colour is a good absorber of heat while white colour is a poor absorber. Temperature plays a significant role in the reduction of induced and skin friction drag**.** Albatrosses fly towards regions with warmer climate during migration. Therefore we can expect an increase in solar radiation. The top part is exposed to solar radiation and atmospheric radiation whereas the bottom part is exposed to atmospheric radiation and oceanic radiation. During the day, due to intense solar radiation the drag on the upper part decreases due to the dark colorization and hence it experiences lesser drag as compared to the lower part. At night, however, the situation reverses and the drag experienced by the lower part are comparatively less. This happens due to the fact that at night in the absence of solar radiation on the upper surface and the presence of oceanic radiation acting on the lower part plays a more influencing role. The net drag of their entire migratory journey is however reduced as they travel to regions having a warmer climate [19].



Figure 8: Irradiation on the wings of albatross [17]



Figure 9. The albatross's wings colour [23].

Drag forces of an albatross wing using Blasius solution for heated laminar boundary layer showed temperature difference between the upper and the lower surfaces to be at least 10 degree Celsius. The drag as mentioned earlier is reduced irrespective of the weather conditions [20]Drag reduction improves efficiency. The colors of an albatross combined with their migrating season are an important factor of their efficient flight performance. Results showed 8 percent drag reduction for a maximum temperature while altering the wing colours from light white to dark black. Dark colour exhibits less drag and hence increased efficiency [21]. colour combinations of wings that were black-black and black-white provided a better performance as compared to colour combinations of wings that are white-white and white-black. Even though the trend observed during the day got reversed during the

night, the black-black and black-white colour combination yielded a better overall performance. This was due to the fact that albatrosses migrate to regions with warmer climates [22].Temperature differences analysis carried out on black-white wings showed that black colours can attain temperatures over 50% higher than white colours and these wings can reach temperatures which are higher than plates of aluminum having the same or similar colours. These wings were also found to be quite efficient for operations carried out at low angle of attack due to this thermal boundary layer performance [23].

2.5. Navigational and Foraging Strategies of an Albatross

Albatrosses have very efficient navigational abilities which enable them in foraging and migration. They can locate remote sites for breeding using different navigational strategies. Even though odour is a major contributor to high navigational efficiency in other Procellariform seabirds; it is not a primary source of information in the case of albatrosses. Wind conditions and inherited genetic encodings play important roles in an albatross's migration cycle [24]. Albatrosses have a well developed system of olfaction. Their large olfactory bulbs are used to detect fishy-smelling odorants in water and air. A crosswind is favorable for an albatross as it increases the probability of encountering odours and hence the albatross has adapted its search techniques for maintaining a stable flight in crosswind conditions. Preference is given to an orthogonal or oblique movement to the flow direction. On encountering a discontinuous odour filament or a scented eddy, the bird will try to stay within the boundary of the odour. If it loses the odour or moves away from the odour boundary, it will exhibit turns or upwind zigzag movements till it manages to re-enter the odour boundary. Both visual and olfactory cues play important roles in prey detection or foraging. Approaches of foraging could be of direct or circular types. Direct approaches generally occur during crosswinds. Circular approaches are mostly used at night. Direct approaches used during the day results in greater preys being caught both in terms of numbers and sizes. Albatrosses in most cases, during a direct approach, catch prey by flying crosswind in a straight line. Their path of foraging remains more or less constant before and after prey capture. This method of flying crosswind is energy efficient and inexpensive and it also increases the probability for catching more prey items by detecting them with olfactory search techniques. These prey items may or may not fall in their flight path. During the night the sit and wait strategy is mostly used, not necessarily to track prey but rather explore a potentially productive area based on factors like visual cues, odours, presence of other birds and types of prey available at night. The bird flies upwind from its resting position if any prey is detected [25].In most birds the tubes or nostrils run along the top of their bills but in all albatrosses, their tubes run along the sides of their bill. They can efficiently measure the airspeed which is crucial for dynamic soaring. These tubes are equivalent to pitot tubes in an aircraft**.** Food habits of albatrosses, specifically the grey headed and black browed albatross mainly include fish, squid and krill [26].

2.6. Atmospheric Effects on the Flight of Soaring Birds

Soaring birds like an albatross, rely mainly on atmospheric phenomena, such as wind and wave properties in case of soaring seabirds. Therefore atmospheric currents play an important role in their choice of migratory routes, foraging areas and breeding locations. As the efficiency of a bird's migration gets affected by weather conditions, this also impacts the bird's breeding and in turn its population distribution. Horizontal winds may either increase the flight speed or hinder migration depending on its direction. The bird's response will impact its migration success. The vertical wind is used by birds to attain the necessary height with less energy usage [27]. Based on atmospheric conditions[28], birds switch between modes of soaring and flapping. Atmospheric updrafts and shear-induced turbulence benefit birds while soaring by acting as an additional energy source. Atmospheric turbulences may be caused by flow interruption due to topography of any terrain [28]. Variable weather conditions can act as supplementary lift generation agents for soaring birds. Orographic lift due to horizontal winds being deflected by a terrain's topography. Thermal lift due to rising air columns produced as a result of solar radiation heating up flat lands. Wind-wave energy used as an external propulsive unit. All these act as supplementary units for soaring birds [29]. Albatrosses fly across headwinds more often as compared to other Procellariformes and avoid tailwind flights. The

relation between aspect ratio and wing loading is significantly positive for albatrosses. They exhibit high values of wing loading and aspect ratio among Procellariformes. The idea behind avoiding tailwind flights is to increase their prey detecting probabilities. Flying upwind aids in maintaining a slow ground speed and also reduces response time during prey detection. The bird does not have to backtrack and also a greater ground speed will decrease the efficiency of their prey detection capabilities [30]. Albatrosses due to their high values of aspect ratio and wing loading have low values of drag and are fast flying birds. They tend to glide and soar more than they flap.



Figure 10: The wing of an albatross [9]

2.7. Limitations due to Hereditary Evolutions

Hereditary evolutions in terms of morphology have led to albatrosses being able to make optimum use of wind and wave energies for long migratory and foraging distances. However these adaptations have also created barriers and created some limitations on their bio-geographic distribution and bounded them to oceans where they make use of the suitable wind speed. Their morphology and olfactory traits also have an impact on their breeding [31]. Optimum migration is achieved by efficiently balancing three factors, namely time, energy, and safety based on their genetic coding and their niches. The type of migration track, whether seasonal or daily also plays an important role. Seasonal migration tracks are generally longer than daily migration tracks [32].

2.8. Blended Wing Body and Aerodynamic Performance

A blended wing body is optimum for aerodynamic performance and enables an energy inexpensive flight operation. A near silent flight can also be achieved through a blended body design [33]. The fuselage of the blended wing body has airfoil like characteristics. And since the wetted area is decreased, a decrease in skin friction drag can be observed. A blended wing body exhibits smoother intersections which in turn causes a reduction in the interference drag. Incorporating this with a span wise lift distribution, a substantial improvement can be attained in terms of aerodynamic efficiency [34]. The blended wing body design aids in the lift effort of the entire structure of the body. It increases environmental performance and helps decrease the stress produced in the wings. It also enhances the overall lift to drag ratio. The absence of a tail means measures such as BSLD, proverse yaw and other measures must be incorporated to maintain an overall stability of the body. BWB design also exhibits weight efficiency [35]. Blended Wing Body tends to have a streamlined structure. Structural weight reduction and reduction in bending moments is also achievable [36]. Blended Wing Body is aerodynamically efficient at subsonic speeds**.** Propeller problems can be solved by holding the maximum Coefficient of Lift to a certain point and then tapering it to nothing at the end point. This will aid in noise reduction. Also if the tips are heavily loaded, they may go supersonic and build shockwaves. Therefore no load must be there at the propeller tips.

3. Conclusion

The aerospace industry has improved a lot in the past few decades and bio-mime tics has been one of the areas to have been explored extensively. Studying about the albatross's traits and evolutions and incorporating it with the latest technology in hand can pave a way for design and manufacture of bionic drones with higher values of endurance and range with minimal fuel intake. If the traits of albatross can be mimicked to near-perfection, we could be looking at near-perpetual versions of bionic drones.

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