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Insights on the thermal impacts of wing colorization of migrating birds on their skin friction drag and the choice of their flight route

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ABSTRACT

The thermal effects of wing color in flight is investigated in four species of birds with respect to their flight routes, migration time, and geometric and behavioral characteristics. Considering the marine and atmospheric characteristics of these flight routes, a thermal analysis of the birds' wings is performed during their migration. The surrounding fluxes including the ocean flux and the solar irradiance are considered in an energy balance in order to determine the skin temperature of both sides of the wing. Applying the Blasius solution for heated boundary layers, it is shown that the color configuration of these migrating birds, namely black on the top side of the wings and white on the bottom side of the wings ("countershading"), results in a skin drag reduction, if compared to some other configurations, when both day and night are taken into consideration. This drag reduction can be considered as one of the effective factors for long endurance of these migrating birds. This research can provide the evolutionary perspective behind the colorization of these migrating birds.

1. Introduction

Nature is the best teacher to design efficient and optimized systems. Epochs of evolutionary trial and error have produced efficient solutions to natural problems that can gainfully inform modeling and engineering of bioinspired designs (Hassanalian and Abdelkefi, 2017; Hassanalian et al., 2017a, 2017b; Hassanalian et al., 2016). Yet there are many factors affecting the structure, behavior, and flight characteristics of birds and insects that must be investigated to achieve this end. Bird color varies widely in accordance with species, age, sex, and many environmental and behavioral factors (McGraw, 2006). One aspect of the birds' coloration that has been largely unstudied to date is how its thermal properties may affect flight performance (Hassanalian et al., 2017c). Hassanalian et al. (2017c) have recently studied the thermal effects of migrating birds' wing color on their flight performance as a new effective parameter on their endurance.

Dynamic soaring and low altitude flight over water are important factors for maintaining long flights by pelagic seabirds, the undisputed champions of long distance migration. Dynamic soaring is a behavior in which energy is gained by repeatedly crossing the boundary between air layers with significantly different velocities (Richardson, 2011; Pennycuick, 2002; Rayleigh, 1883; Sachs et al., 2013). Besides dynamic soaring, wing color can be considered an effective parameter in flight performance. Many birds that implement dynamic soaring over water exhibit counter shading, i.e., dark color on the dorsal (top) side of their wings and light color on the ventral (bottom) side (Hassanalian et al., 2017c). That is generally the case for the wandering albatross, sooty tern, Manx shearwater, and black skimmer. The former three fly in the boundary layer of oceans and are considered as high endurance fliers (Spear and Ainley, 1997). The black and white colors of the upper and under-wings of these species absorb heat at different rates. A black colored material is an excellent absorber and convector while a white one is an excellent reflector but very poor absorber. Therefore, the black surface of the bird wing should heat up more than the white surface. In a previous study, Hassanalian et al. (2017c) considered an albatross wing as a flat plate which was insulated from the bottom side using an adiabatic boundary condition and the temperature of the top surface of the wing was calculated through an energy balance. Two colors, namely, white and black were considered to study their thermal effects. In that study, the top part of the bird wing was considered as the most important part to model since it is the part exposed to the solar radiation. Therefore, for simplicity, the wing was assumed to be insulated from the bottom, and then the Blasius solution was used for the heated boundary layer at constant properties to calculate the wing skin

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drag (Hassanalian et al., 2017c).

In this work, the idea is extended and the modeling is closer to reality since the bottom side of the wing is also considered. We first investigate the migration routes including the latitudes and longitudes, the time of migration, and then the corresponding marine and atmospheric characteristics, such as wind speed, ambient temperature, ocean temperature, and sky temperature of their flight routes of the four aforementioned species. The thermal effects of top side and also the bottom side of the wing with two different colors (white and black) are studied. The effects of the ocean and sky radiation are investigated in the energy balance for both sides of the wing. The main objective of this study is to investigate the functional significance of wing color under the assumption that it is optimally adapted, and propose the best colors for the design of drones to decrease their drag forces and increase their endurance. The rest of this paper is organized as follows. The features, flight routes and migration time of the birds are discussed in Section 2. In Section 3, corresponding marine and atmospheric features of the routes are extracted. Modeling and thermal analysis of the migrating birds' wings and Blasius boundary layer are described in Sections 4 and 5, respectively. The calculation of skin friction drag for migrating birds and comparison of different arrangements of black and white colors for the wings are shown in Section 6 and 7, respectively. Summary and conclusions are given in Section 8.

2. Characteristics of the study organisms

Wandering albatross, Manx shearwater, sooty tern, and black skimmer are considered in this study.

Albatrosses and shearwaters are large and medium sized members of the order Procellariiformes, respectively. Procellariiformes are collectively characterized as tubenoses. They are so specialized for epipelagic (above the open ocean) life that they drink only seawater and expel concentrated salt from their tubular nostrils. They only come to land to breed, and then only after many years before reaching sexual maturity and not necessarily every year. Some, if not all, even sleep on the wing (Oceanwide Expeditions, 2017). Most pertinent to this study, procellariiforms represent the pinnacle of non-powered endurance flight among birds. In general, procellariiforms forage by surface feeding or foot-propelled diving for aquatic prey, in which case they stop flying if only briefly. Morphological adaptations for their prolonged flight include wings of very high aspect ratio, high loading, and a disproportionately long proximal wing and short distal wing. The proximal wing (brachium and antebrachium) supports tertial and secondary remige feathers, which are primarily responsible for lift. The elongated proximal wing of procellariiforms maximizes lift while their short secondary remiges (represented by chord) minimize drag. The distal wing (manus) supports primary remige feathers, which are primarily responsible for propulsion in typical birds. Muscle biochemistry, muscle insertions, and joints are also adapted for prolonged wing extension without flapping in procellariiforms. The tail of birds is used primarily as a rudder for steering but it also generates lift and significant drag. The very short, stiff, and wedge-shaped tail of procellariiforms probably generates little of either. The contour (body) feathers of procellariiforms are short and dense for thermoregulation and water resistance.

(1) *Wandering Albatross* (*Diomedea exulans*) Albatrosses (family Diomedeidae) are the largest of the tubenose seabirds (order Procellariiformes), and among the largest flying birds, with wingspans reaching up to 3.5 m. Individuals of different sexes and populations differ considerably in size. They have highly efficient flight because they adopt dynamic and slope soaring (Richardson, 2011; Pennycuick, 2002; Rayleigh, 1883; Sachs et al., 2013). Albatrosses are able to cover great distances with little exertion. They can be found widely in the North Pacific and Southern Ocean. These seabirds are capable of traveling 10,000 miles without expending any energy (Hassanalian et al., 2017c). Albatrosses perform a highly dynamic maneuver that involves gaining height by angling their wings while flying into the wind, then turning and diving up to 100 m (Richardson, 2011; Sachs et al., 2012). The low-cost flight of this migrating bird has attracted the attention of drones' designers in order to design efficient and high performance drones (Hassanalian et al., 2017c). NASA has looked at dynamic soaring as a way to power unmanned aircraft that could carry out atmospheric and oceanic research or monitor fisheries for months at a time (McGraw, 2006). Besides the dynamic soaring as one of the main reasons for long flight of these migrating birds, the color of their wings also can be considered as an effective parameter in their flight performance. Albatross wings are generally black dorsally (above) and white ventrally (below). However, both the upper and undersides of the wings of immature birds are dark, and the upper wing gradually becomes whiter with age, especially in some populations.

(2) *Manx Shearwater* (*Puffinus puffinus*) Shearwaters are intermediate sized Procellariiformes of the family Procellariidae. The Manx shearwater has long straight slim wings, black upper wing and white underwing, length of 30–38 cm, wingspan of 76–89 cm, and a weight of 350–575 g (Hoyo et al., 1992, 1996). Shearwaters generally fly with a series of rapid stiff-winged flaps which are followed by long glides on over the surface of the ocean, occasionally banking or shearing, which consists of flying very close to water and seemingly cutting the tips of waves to move across wave fronts with the minimum of active flight. Shearwaters breed in colonies in the UK, on offshore islands where it is safe from predators. These birds leave their nest sites in July, to migrate to the coast of South America, where they spend the winter, returning in late February and March (rspb, 2017; Lieberknecht, 2014). Electronic tags, such as GPS have shown the mysteries of the 20,000 km migration of Manx shearwaters. The flight speed of these migrating birds ranges from 12 to 16 m/s, depending on wing configuration and flap rate (Ito and Ogi, 1999).

Terns and skimmers are small members of the gull family (Charadriiformes: Laridae). They are distinguished from gulls by their generally smaller size, straight bills, longer more pointed wings, and mildly to deeply forked tails. Larids rely more on powered flight than procellariiforms, and terns even more so than gulls. The wings of larids, and terns in particular, are constructed very differently than that of procellariiforms, despite their relatively high aspect ratios. The distal wing, responsible for propulsion, is greatly exaggerated and lengthened and the proximal wing, responsible for lift, is relatively short. Their long forked tails and longer and looser contour feathers also differ from those of procellariiforms. In general, terns are graceful fliers and low altitude plunge divers, during which time they get no respite from flight. However, most terns regularly rest on land, floating substrates, or on the water surface. Skimmers are basically terns named for their unique method of foraging, in which they fly literally at the water's surface with their oversized blade-like bill dragging through the water in search of fish. Because these birds must forage exclusively in the very shallow still water of back bays, estuaries, and rivers, they are exclusively powered fliers. Unlike terns, they are entirely neritic, never venturing into the open ocean, despite their wings of higher aspect ratio.

(3) *Sooty Tern* **(***Onychoprion fuscatus***)** The sooty tern measures33–36 cm in length, wingspan of 82–94 cm, and a weight of 150–240 g. The wings and deeply forked tail of these birds are long and they have dark black color in upperparts and white color in underparts of their wings (Flint and Nagy, 1984). The average life span of these birds is 32 years. Sooty terns are the most epipelagic long endurance fliers of all the terns. It is noted that they rarely rest even on the water surface. Like albatrosses, they can sleep while flying (Oceanwide Expeditions, 2017). Immature sooty terns stay at sea for 3 years before returning to breed (Pettingill, 2013). Although