Bio-inspiration in the Wings of Man-made Flyers

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Abstract

Natural flyers have been excellent prototypes of various air vehicles. A lot of efforts have been put into mimicking bio-flight mechanisms in order to achieve similar aerodynamic performances such as lift and thrust enhancement and high stability with minimal power consumption. This article reviews a wide range of biologically-inspired air vehicles, focusing on the analogy between the wings of nature-made and man-made flyers.

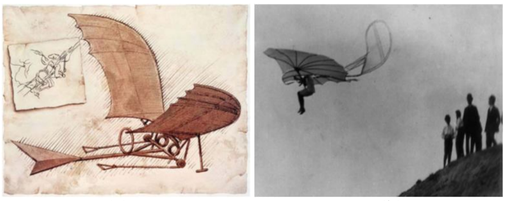
Keywords: Bio-inspired, Biomimetics, Micro air vehicle, Flapping wing, Insect flight

1. Introduction

The great agility and maneuverability of natural flyers have drawn substantial attention from air vehicle designers and engineers. Inspiration from distinct features of the biological wings has influenced the wing designs of various man-made vehicles. From as small as ‘pico’ air vehicles, Nano Air Vehicles (NAVs) and Micro Air Vehicles (MAVs) to larger Unmanned Aerial Vehicles (UAVs) and human-powered hang gliders, many attempts have been made to improve the vehicle performance using concepts such as fixed wings and flapping wings found in nature. This paper reviews the biologically-inspired vehicles starting with the most prevalent imitation associated with bird wings, for which flapping motion has been a considerable influence. Next, for fixed-wing vehicles where the use of compliant membrane wings has recently been of great interest, those motivated by astonishing flights of flying mammals such as bats, and flying reptiles such as pterosaurs are discussed. Finally, various models especially insect-sized ones inspired by tiny wings of insects are explored.

2. Bird-inspired wings

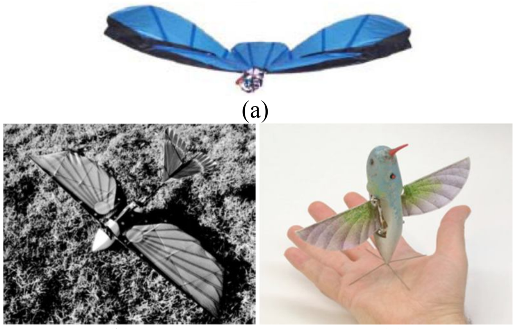
Historical influence of bird wings on man-made vehicles was observed in Leonardo da Vinci’s studies of continuity of a fluid and aerodynamic forces over a bird wing [1]. One of his designs, a sketch of a human powered flapping wing vehicle, is shown in Fig. 1a. Early researchers, such as Otto Lilienthal, were convinced that emulating bird flight was the key to fly heavier-than-air vehicles [2]. From the study of bird wings, he built a large glider as shown in Fig. 1b and flew successfully. Although stability and control was a problem of glider flights back then, it was solved later by the Wright brothers.



(a) (b)

Fig. 1 Historical influence [3]: (a) Leonardo da Vinci’s human-powered ornithopter design; (b) Otto Lilienthal's successful gliding attempt

Bird wings not only move forward relative to the air, but also flap up and down, plunge, and sweep [4]. Flapping flights of birds, in particular, have received great attention from biologists, aerodynamists and aircraft designers. In contrast to conventional fixed wings, the flights of flapping wings are inherently more complicated. The fluid unsteadiness, interacting with wing kinematics and shapes determines the lift generation [5]. Aerodynamics of flapping wings, including leading-edge vortices, pitching-up rotation and wake-capturing mechanisms was intensively investigated by researchers such as Shyy et al [4] and Viieru et al [5]. A great number of flapping-wing MAVs has been designed and developed from inspiration from flapping flights of birds. A few examples are shown in Fig. 2.



(a)

(b) (c)

Fig. 2 Examples of flapping-wing air vehicles mimicking the flapping flights of birds: (a) Ornithopter from the University of Maryland [6]; (b) a 74-cm ornithopter from the University of Arizona [7]; (c) AeroVironment’snano hummingbird

Besides flappings, bird wings also sweep back as can be seen by a swift shown in Fig. 3a. The swifts can stay in the air for a very long time, hunting insects at day, roosting in flight at night, and even mating in the air. They are known to fly non-stop for over a whole year [1], covering 4.5 million kilometers over their lifetimes. Motivated by these efficient flyers, a team from the collaboration between TU Delft and Wageningen University has developed a RoboSwift (Fig. 3b,c), a MAV which is able to fold the wings backwards, thus changing its swept angle and wing surface area, therefore

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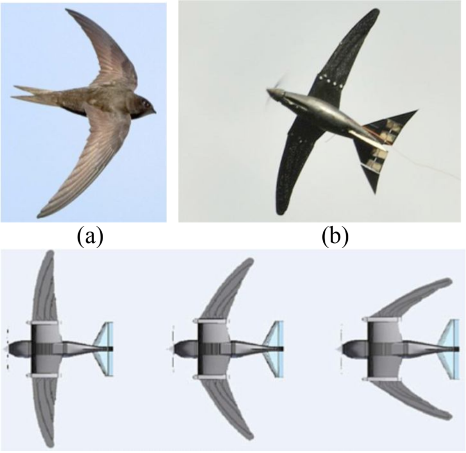
enhancing the performance envelope [8]. The vehicle steers by sweeping back one wing more than the other.


(a) (b)

(c)

Fig. 3 From swift to swift-inspired MAV: (a) A common swift in flight [9]; (b) A "RoboSwift" developed by the Delft University of Technology and the Department of Experimental Zoology of Wageningen University; (c) The RoboSwift's wings folding backwards, influenced by the real animal

More recently, great maneuverability and gliding ability of a swift has also inspired Thielicke [10] to design an energy efficient flapping-wing MAV as seen in Fig. 4. When completed, the vehicle is expected to be able to slow its flight when needed, and maneuver in confined spaces.

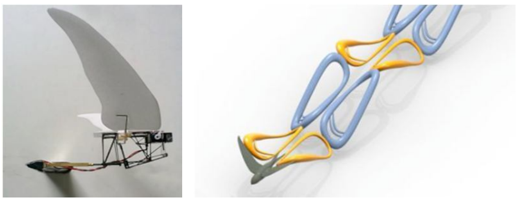


Fig. 4 MAV model inspired particularly by swift, hoping to improve energy efficiency beyond normal fixed wing MAVs. Also shown is the impression of the wake in slow forward flight [10]

It is known that most owl species fly quietly for their hunting strategy [11]. Inspired by a special feature of owl's wings,the capability of flying silently, a study of the flow field over an owl based airfoil was carried out by Klän et al. [12] with an aim to ultimately design a silent airfoil. As seen in Fig. 5, an owl wing has three main characteristics, defined as a velvet-like surface, leading-edge serrations and trailing-edge fringes [13]. The study [12] suggested that by applying velvet onto the suction side, the size of separation at moderate angles of attack could drastically be reduced.

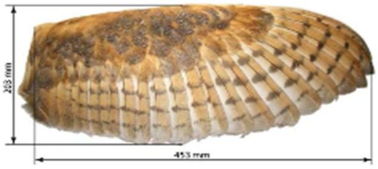


Fig. 5 An owl wing, the inspiration for researchers to design 'silent' airfoil [12]

3. Flying mammals and flying reptiles-inspired wings

A growing interest in the use of membrane wings for MAVs is particularly inspired by flying and gliding mammals such as bats (Fig. 6a). Bats have thin compliant wings as lifting surfaces, and exhibit high maneuverability. It is suggested that bat flight might be more efficient than that of large insects or small birds at comparable size [14]. The skin of the bat wing is known to exhibit substantial changes in shape and camber throughout the wingbeat cycle [15]. To understand the aerodynamic effects of membrane compliancy on bat flights for MAV applications, Galvao et al. [16] conducted an experimental study on a membrane wing made from latex. Their results indicated steeper lift slopes and higher power efficiency due to adaptive cambering in of the membrane wing compared with those of a rigid wing. Advantages of membrane wings were also illustrated in the studies carried out intensively by a research group from the University of Florida. Examples of their membrane wing MAVs are shown in Fig. 6b. It was found that the membrane could significantly improve longitudinal static stability, provide more favourable lift to drag ratio and gust rejection, and delay stall [4, 17-24]. At the same freestream velocity and angle of attack, both experimental studies [25-27] and numerical study [28] showed that a membrane airfoil exhibited smaller separated region. Additionally, as illustrated in Fig. 7, the excitation of the roll-up of large vortices was found over the membrane surface at high angles of attack, whereas the flow was fully separated for a rigid counterpart.


(a) (b)

Fig. 6 Compliant membrane wings: (a) Membrane wing of bats [29]; (b) University of Florida's reinforced membrane wing MAVs

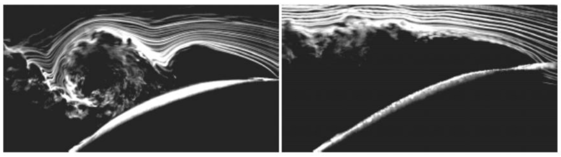
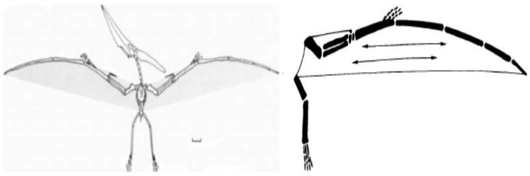

(a) (b)

Fig. 7 Smoke visualization comparing the flow over a membrane (a) and rigid (b) airfoil [25] (flow is from right to left)

As the earliest vertebrates known to have evolved powered flight, Pterosaurs were subject of interest by aerodynamists, dating back to as early as more than a century ago [30-37]. Flight performance of the animal was widely studied. Its wing, in particular, had an influence on wing designers of powered aircraft at that time. Pterosaurs had a thin membrane cambered wing with a large spar near the leading-edge as seen in Fig. 8, which was known to be aerodynamically stable with respect to pitching moments [38].



(a) (b)

Fig. 8 Flying reptiles: (a) Drawing of a pterosaur from the Smoky Hill Member of the Niobrara Limestone of western Kansas, modified after Williston [39]; (b) Drawing of a pterosaur wing with arrows indicating the main direction of membrane tension [40]

Wing loading and aspect ratio of the pterosaurs were summarized by Brower and Venius [41]. Such parameters indicated the animal's flying and gliding speed and induced drag. The wing skin was a membrane-type, in which tension was approximately in a spanwise direction [40]. The flexibility of the membrane, together with movements of the wing bones, allowed the pterosaurs to control the camber and angle of attack of the wing, leading to great maneuverability in low-speed flight. Relating to man-made flyers, Princeton Sailwing and Sailvane wings were closely similar to those of pterosaurs [42-46]. As seen in Fig. 9, the membrane wing of the vehicle was attached to a leading-edge spar, and the trailing-edge was formed by a wire under tension. By adjusting the tension of the wire, the camber and twist of the wing could be altered. Additionally, the tension exerted on the membrane prevented luffing of the wing. Due to such analogy and the fact that both pterosaurs and hang-gliders had low wing loading and low flight speeds, it was suggested that they shared a similar range of lift and drag coefficients [40].

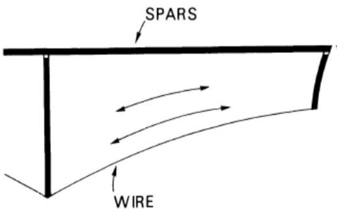
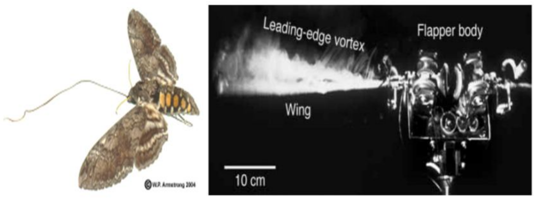


Fig. 9 Hang-glider wing design of Princeton Sailwing [44,46]: the spanwise tension of the wing was controlled by a wire at the trailing-edge

4. Insect-inspired wings

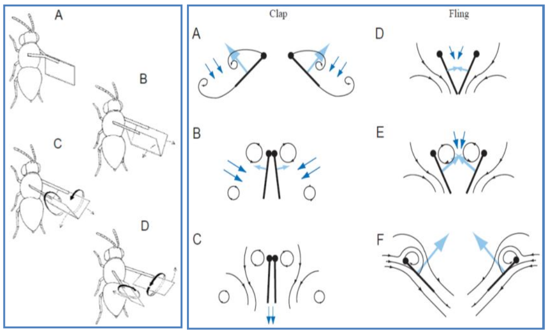
Flight mechanism of insects has greatly motivated air vehicle designers, especially when the size of the vehicle is of main concern. The flight control processes of insects are simpler than birds and bats, which possess active musculature along the span of the wing [47]. A relatively small wing area of insects must produce adequate lift to support the body weight. This can be achieved by having high wing beat frequency. Most insects take advantage of a spiral leading edge vortex (LEV) created by dynamic stall during flapping to enhance lift. A LEV is commonly present for thin wings with sharp leading-edges operating at high angles of attack. Flow visualization on a mechanical model made to mimic a large hawkmoth*Manducasexta*, shown in Fig. 10a, carried out by van den Berg and Ellington [48] demonstrated a LEV over a wing during the downstroke as seen in Fig. 10b. Following, in an attempt to provide a design for flapping wing MAVs, Ellington [49] also presented the detailed aerodynamic characteristics of the same insect-based flying machine.



(a) (b)

Fig. 10 Hawkmoth-inspired: (a) An adult hawkmoth*Manducasexta* [50]; (b) Leading-edge vortex seen over a wing during the downstroke of a hovering hawkmoth model [48]

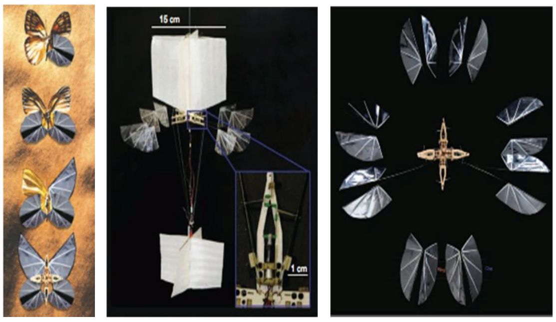
While it is well-known that LEV generates lift for flapping-wing insects, some insects rely on slightly different wing motion for enhanced lift production. They clap the wings together and fling open before the downstroke, known as fling mechanism shown in Fig. 11a. The clap-and-fling motion was originally described by Weis-Fogh [51]. Such motion creates a bound vortex which then acts as a starting vortex. When the wings fling open, an air rushes in to fill the gap (a low-pressure region) between them, giving attached vorticity as shown in Fig. 11b. The circulation created by the fling results in lift enhancement.



(a) (b)

Fig. 11 The clap and fling mechanism: (a) The clap and fling of the tiny wasp *Encarsiaformosa*. The wings clap together at the end of the upstroke and then fling apart before the downstroke, creating a bound vortex which generates extra lift [52]; (b) Schematics of the wings with light blue arrows indicating net forces and dark blue arrows showing induced velocity [53]

Taking advantage of the clap and fling mechanism, van Breugel et al. [55] designed a flapping-hovering MAV, which consisted of four pairs of wings as shown in Fig. 12. Wing pairs were able to bend passively during flapping, increasing the amplitude of the flap. The passive stability of the vehicle was also verified by its ability to recover from arbitrary launch orientations.



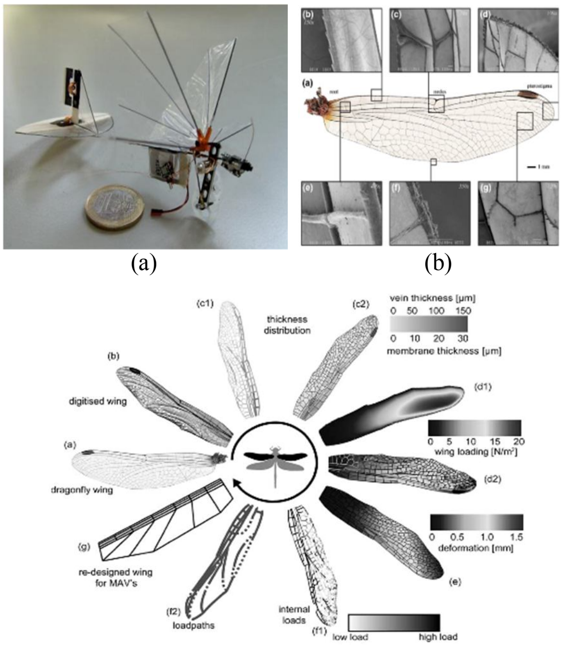
(a) (b) (c)

Fig. 12 Flapping-hovering MAV of van Breugel et al. [54,55] inspired by both insect wings and hummingbird flight: (a) Impression of the wing design inspired by a butterfly; (b) The vehicle of which the wings flap symmetrically, with opposite wing pairs reversed to reduce asymmetry effects; (c) Top-view of aeroelastic wing bending (adapted from van Breugel et al. [55])

Having researched and gained insight on insect flight in the lift enhancement mechanisms involved with flapping wings, a team at the Delft University of Technology has developed a series of flapping wing MAVs called DelFly, shown in Fig. 13a. Comparable to insect wings, the wings of the vehicle are actuated at the wing base. The instantaneous shape of the wings depends on the interaction of aerodynamic, inertial and elastic forces, which involve parameters such as angle of attack, location of the axis of rotation and leading edge heaving motion [56]. Like clap and fling effects stated by Weis-Fogh [51], when the wing moves apart, the air is sucked into the low pressure region in the opening gap and a starting vortex is generated from circulation within the wing proximity. The wing flexing corresponds to a large increase in lift, which was found greater during the fling than clap motion [56]. Further inspired by the front wing of a dragonfly *Sympetrumvulgatum*, the corrugated wing of the MAV was re-designed [57,58] based on the wing and flight data of the real animal (Fig. 13b,c). The corrugation height decreases towards the wing tip, and can be aeroelastically tailored to improve effectiveness.

Complex vortex interaction between the two wings of dragonflies was believed to benefit the animal flight [59,60]. Unlike a single pair of flapping wings, wake interaction is expected from tandem-flapping wings. This idea motivates aircraft designers to utilize the right phasing of the tandem flappings to reduce the vertical oscillatory force imposed on the fuselage [61]. Thrusts and propulsive efficiencies of a tandem-wing ornithopter shown in Fig. 14 were investigated by Warkentin and DeLaurier [62]. The tandem arrangement, including the wing flapping frequencies, flapping phase angles and distance between the wings, which give the ornithopter the best performance was identified in their study.

In an attempt to make a flying machine that is useful for exploration, search and rescue, and surveillance for the battlefield and urban environments without being noticed, Harvard's Microrobotic Fly (Fig. 15) is the first insect-sized MAV inspired by Dipteran insects capable of vertical liftoff with external control and power [63]. Developed by Harvard microrobotics laboratory, the wing is made from a combination of a thin membrane and rigid veins to imitate the reinforcement structure of most insect wings [64]. While the wing is morphologically similar to insect wings, the veins are arranged to make it extremely rigid for all expected loading conditions [64]. It is claimed to be the highest strength-to-weight ratio of any man-made or biological wing ever created [64]. The wing trajectory is also nearly identical to that of hovering Dipteran insects (Fig. 15b). Each wing is attached to a flexure hinge that acts as a torsional spring. As it is flapped, the spring allows the wing to rotate passively due to aerodynamic and inertial forces. The lift is generated on both the upstroke and the downstroke [65].



(a) (b)

(c)

Fig. 13 Dragonfly-inspired: (a) DelFly Micro (2008) weighing 3 grams is the successor to the previous DelFly I (2005) and DelFly II (2006) developed by Delft University of Technology. It can fly horizontally, fly backwards, as well as hover just like hummingbird; (b) Detailed study of the real fly's forewing structure [58]; (c) The thickness, load distribution and deformation of a dragonfly investigated to help re-design the vehicle wings [57]

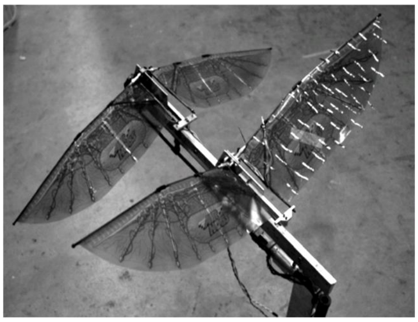
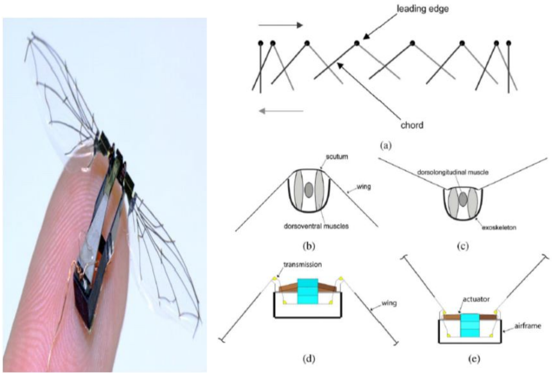


Fig. 14 A tandem-wing ornithopter investigated by Warkentin and Delaurier [62] to find the right tandem arrangement that gives highest thrust and propulsive efficiencies



(a) (b)

Fig. 15 Bio-inspired microrobotic insects: (a) Harvard microrobotic fly with biomimetic composite wings, weighing 60 milligrams with a wingspan of three centimeters [66]; (b) Approximate wing motion showing upstroke and downstroke of a Dipteran insect and a comparable robotic fly [63]

Further, inspired by the biology of a bee and the insect's hive behavior, another insect-sized flapping wing MAV is under development by Harvard microrobotics laboratory research team. This "RoboBee" (Fig. 16) is a "pico" air vehicle (defined as having a maximum takeoff mass of 500 milligrams or less and maximum dimension of five centimeters or less), having two wings capable of controlled thrust and body moments [67].

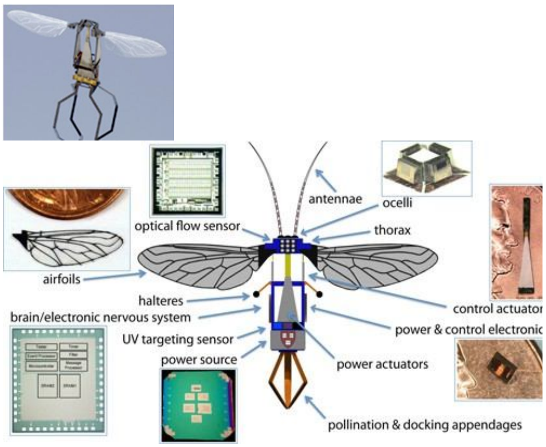


Fig. 16 A 500 mg bee-inspired flapping-wing MAV from RoboBee project, Harvard School of Engineering and Applied Sciences

Like most other insects, bumblebees use a leading-edge vortex for lift production. However, unlike most others, smoke visualization showed that bumblebees shed both tip and root vortices, with no flow interaction between lift and right wings or their near-wakes [68]. Even though these topologies might be aerodynamically less efficient, they could allow the animals to independently control left and right wings [68].

To develop an artificial hoverfly wing, the effect of wing flexibility on lift generation was investigated by Tanaka et al. [69] using an at-scale model as seen in Fig. 17. A polymer wing was compared with a rigid carbon-fiber wing using a flapping mechanism. The compliant polymer wing exhibited less passive rotation around the wing hinge due to smaller effective angle of attack. Their results suggested that for the same flapping motions, a rigid wing could produce larger lift.

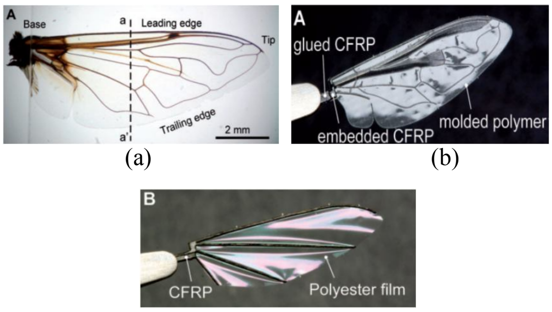


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Fig. 17 Effect of flexibility of hoverfly wing models on lift force studied by Tanaka et al. [69]: (a) Venation of a hoverfly; (b) Polymer corrugated wing; (c) Carbon fiber reinforced wing

Drag polar diagram of a dragonfly forewing was also observed in the work of Wakeling andEllington [70]. As shown in Fig. 18, the animal wing seems aerodynamically insensitive to its operating Reynolds number, which differs from a mad-made counterpart, which displays sensitivity in certain ranges of Reynolds number [71].

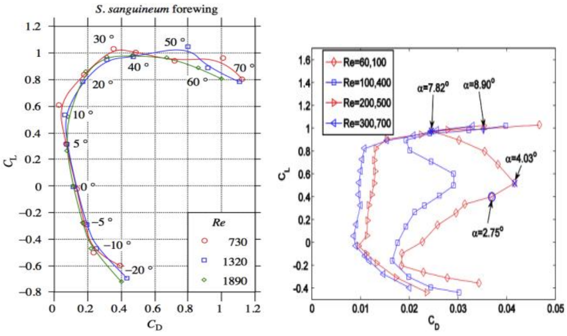

Fig. 18 Drag polar diagram of Sympetrumsanguineum forewing [70] and that of Eppler E374 airfoil [71]

5. Conclusions

Man-made flyers developed from nature inspiration have been reviewed in this article, with emphasis on the analogy between the wings of the vehicles and those of the animals. Various examples were covered, from historic vehicles to future models, and from a minuscule scale to a human-powered size. The sources of inspiration included the flights of vertebrate and invertebrate animals. The author made an effort to review publications from both biological and aeronautical literatures. However, due to the interdisciplinary nature of the subject and the fact that there are countless attempts to build nature-inspired air vehicles to date (both successful and ongoing designs), complete information could not be presented here. It is expected that different aspects learned from techniques used in a wide range of biomimetic flyers given in this paper would facilitate the progress of this fascinating subject.

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