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Propulsion for Biological Inspired Micro-Air Vehicles (MAVs)

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Abstract

Small Unmanned Aerial Vehicles have been receiving an increasingly interest in the last decades, fostered by the need of vehicles able to perform surveillance, communications relay links, ship decoys, and detection of biological, chemical, or nuclear materials. Smaller and handy vehicles Micro Air vehicles (MAVs) become even more challenging when DARPA launched in 1997 a pilot study into the design of portable (150 mm) flying vehicles to operate in D^3—dull, dirty and dangerous—environments. More recently DARPA launched a Nano Air Vehicle (NAV) program with the objective of developing and demonstrating small (<100 mm; <10 g) lightweight air vehicles with the potential to perform indoor and outdoor missions. The current investigation is focused on the mechanisms involved with natural locomotion (propulsion and lift should not be considered independently). Biological systems with interesting applications to MAVs are generally inspired on flying insects or birds; however, similarly to the aerodynamics of flight, powered swimming requires animals to overcome drag by producing thrust. Commonalities between natural flying and swimming are analyzed together with flow control issues as a purpose of improvement on biology-inspired or biomimetic concepts for Micro Air Vehicles implementation.

Keywords

Biomimetics, Flapping Wings, Insect Flight, Adaptive Biology

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1. Introduction

This paper is focused on the mechanisms involved with natural locomotion (thrust and/or lift). Commonalities between natural flying and swimming are analyzed together with flow control issues. The present study has been driven by the ability of living organisms to fit an ecological system in terms of their locomotion. Historically, it was envisaged that men would fly by flapping artificial wings like birds; their physiological and biomechanical

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flapping flight procedures have been explored by men since Giovanni Alphonso Borelli [1]. On the XIX Century, Étienne Jules Marey developed studies about the insects flapping flights and was the first to notice a complex horizontal 8 shape wing motion pattern on its trajectory during the flight. In 1874 Pettigrew Bell published a book [2] on which he drew attention to the fact that the birds while flying and during every cycle of wingbeat, run movements that could be represented with considerable accuracy with an 8-figure drawn vertically, while the insects run the same figure drawn horizontally displaced. In 1902, Pettigrew stated that in a way to confer on the insect's wings the multiplicity of movements which they require, they are supplied with double hinge or compound joints, which enable them to move not only in an upward, downward, forward, and backward direction, but also on several intermediate degrees of obliquity—meaning this that insects wings are actually acting as helices, or twisted levers, and elevating weights much greater than the area of the wings would seem to warrant [3]. Similarly, by studying the fish's species, men found that most of them swim with lateral body undulations running from head to tail, in motion that also remind a 8-shape figure configuration, when viewed from the top (see **Figure 1**).

2. Background

Small Unmanned Aerial Vehicles (UAVs) have been receiving an increasingly interest in the last decades. This interest was fostered by the need of vehicles able to perform surveillance, communications relay links, ship decoys, and detection of biological, chemical, or nuclear materials [4]. Smaller and handy vehicles (Micro Air Vehicles or MAVs) become even more challenging when DARPA launched in 1997 a pilot study into the design of portable (150 mm) flying vehicles to operate in D^3—dull, dirty and dangerous—environments [5]. More recently DARPA launched a Nano Air Vehicle (NAV) program with the objective of developing and demonstrating small (<100 mm) lightweight air vehicles (<10 g) with the potential to perform indoor and outdoor missions [6]. All requirements of low altitude, long flight duration at low speeds (up to 100 km/h), small wing spans and masses, together with demanding capabilities of takeoff, climb, loiter, hover, maneuver, cruise, stealth and gust response are further beyond today's fixed wing or rotorcraft vehicles. At the same time, MAVs fit in the general sizes, weights, and locomotion performance of natural flying or swimming animals [7]. Nevertheless, biomimetic engineered devices are still far from the living organisms and more research is needed [8]. There is a general agreement that an unsteady dynamics approach is required to capture the physical phenomena at this scale [9]. Additionally, propulsion and lift should not be considered independently. Flapping wing systems appeared in animals such as insects, bats, birds, and fishes, which are known to exhibit remarkable aerodynamic and propulsive efficiencies. So, there have been several experimental and numerical studies of the biomimetic propulsive flapping [10] [11]. Most of these studies addressed the role of kinematic parameters such as flapping frequency, amplitude and phase difference on thrust generation and propulsive efficiency. At the same time, the effect of airfoil configuration has been considered far less and the published work is not always in agreement. For example, the results [12]-[14] show that thick airfoils can improve plunging airfoil performance, whereas [15]-[17] suggest than thin airfoils perform better, and the inviscid analysis [16] concludes no influence of airfoil thickness on plunging airfoil propulsion. Some authors attribute the superior efficiency of natural systems of thrust generation and propulsive efficiency to wing flexibility and focused their research on flexible wings with chord and span flexibilities [18] [19]. Has been reported [20] that flapping wings induce three rotational accelerations: angular, centripetal and Coriolis in the air near to the wing's surface, which diffuse into the boundary layer of the wing. Their results suggest that swimming and flying animals could control de predictability of vortex-

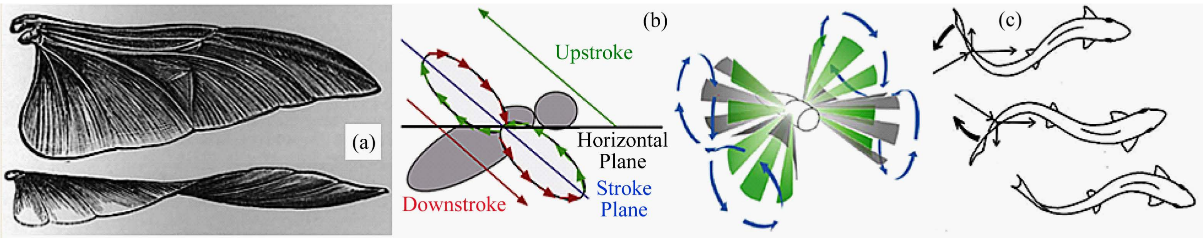

Figure 1. (a) Illustrative examples of the form and deformation of wings alluded to those of the beetle, bee, and fly—Pettigrew Bell [3]; (b) lateral and isometric view of a generic insect wingstroke plane revealing a horizontal 8-shape figure drawn; (c) top view of fish's motion revealing an 8-shape figure drawn.

wake interactions, and the corresponding propulsive forces with their fins and wings. Researchers [21] investigated dimensionless numbers to study swimming and flight, and their findings were disappointing since it became clear that different points of view exist in the biomechanics field on how to best define and use. So, successful biology-inspired or biomimetic concepts will depend on the understanding of the natural mechanisms especially when they do not agree with the present engineering design principles.

3. Some Consideration Related to Fluid Media (Water and Air)

Water and air are both regarded as fluid media, however, they are distinguished from each other: water is comparatively heavy (~1 ton/m^3) and incompressible; air, on the other hand, is comparatively light (~1.225 kg/m^3 at sea level, at 15˚C) and incompressible below Mach number M ~ 0.3 (the ratio of flow velocity/sound velocity must be greater than ~0.3 for a change fluid density of >5%); for M > 0.3, significant compressibility occurs; all insect's fly in an incompressible air flow. When an animal swim through the water, the drag obtained is much greater when compared with the drag obtained from air similarly treated. Unsteady water flows are very common in nature, yet the swimming performance of fishes is typically evaluated by researchers, at constant, steady speeds at an appropriate facility. Similarly, most studies of insect flight are conducted in smooth flow or still air conditions. On both cases, it is still mostly unknown if unsteady water flows represent advantages and/or disadvantages to swimming fishes, and as well, if variable wind in nature affects flying insects as an advantage and/or disadvantage; however, in order to meet such peculiar requirements, all traveling organs of aquatic and flying animals (feet, fins, flippers, or wings) are not designed by nature as of rigid materials; instead, they are elastic materials.

4. Swimmer Organisms: Locomotion on Fish: Tail and Fins—Control Surfaces

Most fish species swim with lateral body undulations running from head to tail, by exerting force against the surrounding water; these waves are slower than the waves of muscle activation; *i.e.*, they contract muscles on either side of its body in order to generate flexion waves that travel the length of the body from head to tail. Fish's body is often fusiform, a streamlined body plan often found in fast-moving fish. They may also be filiform (eel-shaped) or vermiform (worm-shaped). Also, fish are often either laterally thin (compressed), or dorsoventrally flat (depressed). Their muscle power is converted to thrust either directly by the bending body or almost exclusively by the tail, depending upon the body shape of the species and the swimming kinematics. Comparative scientists (physiologists and neurobiologists) have long been interested to realize how locomotion mechanisms used by aquatic organisms, propel themselves through water. The main external features of the fish are fins, composed of bony spines protruding from the body with skin covering them and joining them together; and as they are located at different body's places on the fish, they serve as well for different purposes, such as moving forward, turning, and keeping an upright position. Dorsal fins are located on the back: most fishes have one dorsal fin, but some fishes have two or three (as well as also could have finlets—small fins, generally between the dorsal and the caudal fins). The dorsal fins serve to protect the fish against rolling. The caudal fin (tail) is located at the end of the caudal peduncle and is used for propulsion. The tail fin can be: rounded at the end; truncated; forked; emarginated; or continuous. The anal fin is located on the ventral surface and is used to stabilize the fish while swimming. The pectoral fins are located on each side of the fish. A peculiar function of pectoral fins, highly developed in some fish, is the creation of the dynamic lifting force that assists sharks, in maintaining depth; they also enables the "flight" for flying fish and the "walking" in some anglerfish in the mud. The ventral fins assist the fish in going up or down through the water, turning sharply, and stopping quickly. Torsional angles changes on fish's fins can be produced by active control, via muscles force, or by passive control, via inertial hydrodynamic forces (**Figure 2(a)** and **Figure 2(b)**). Extensive studies have been made on the Dolphins [22]; their fusiform and streamlined body shape, reduce the pressure component of the drag through maintenance of laminar flow; their maximum thickness (where transition to turbulent flow and boundary-layer separation is likely to develop) it is nearly at 45% of a body length from the beak, meaning that at least 45% of dolphins body may have laminar flow, due to a favorable pressure gradient up to the maximum thickness. The dolphins fineness ratio (FR = body length/maximum diameter) may range among the values $3.85 \leq FR \leq 5.55$ close to the optimum value of lowest drag of FR = 4.5 (e.g. [22]). Their propulsive movements are confined to the vertical plane in the posterior 1/3 of the body, with greatest amplitude at the caudal peduncle; the anterior body part acts as an inertial mass, minimizing energy loss from body oscillations. Dolphins could perform maxi-

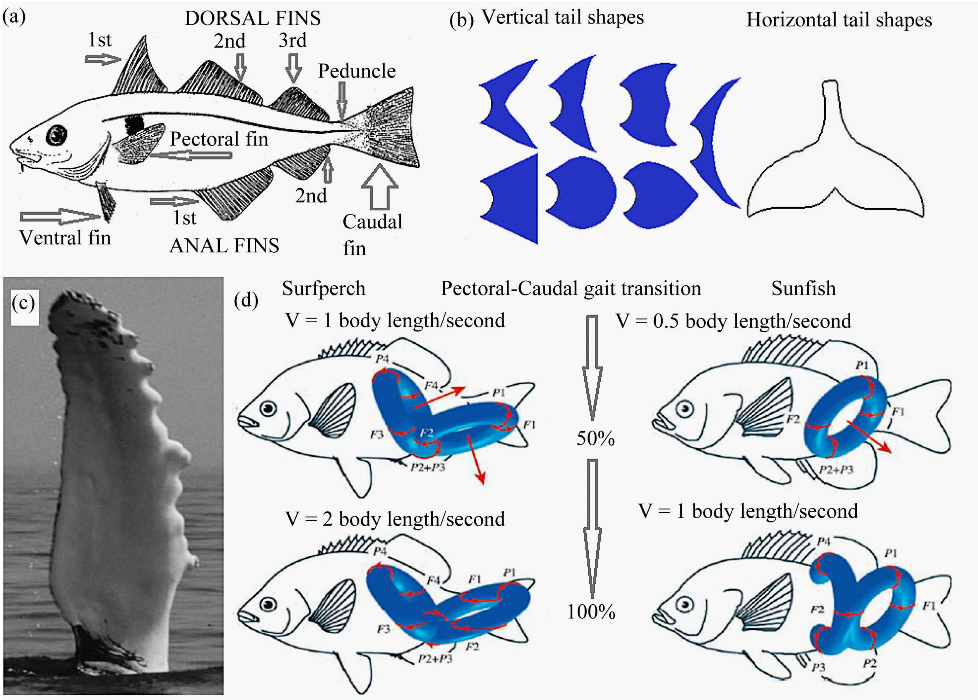

Figure 2. (a) Control surfaces on a generic fish; (b) Different types of fish fin tails known; (c) Photo of a pectoral flipper of the humpback whale (*Megaptera novaeangliae*) show leading edge tubercles [23]; (d) Black surfperch (*Embiotoca jacksoni*) and Bluegill sunfish (*Lepomis macrochirus*), revealing vortex rings at different speeds [25].

mum speed up tom 9.3 ms^{-1}. *Orcinus orca* could perform maximum speed up to 15.5 ms^{-1} during 20 minutes. The pectoral flippers of the humpback whale (*Megaptera novaeangliae*) show leading edge tubercles [23] as illustrates **Figure 2(c)**. Comparisons of wing sections with and without tubercles using CFD models, showed a 4.8% increase in lift; 10.9% reduction in induced drag; 17.6% increase in lift to drag ratio for wing section with tubercles at 10˚ angle of attack. Enhanced maneuverability by the addition of leading edge tubercles has potential application in the development of modern vehicles operating in air or water. Experimental flow visualization [24] compared with numerical simulations on both velocity and vorticity fields, revealed a good agreement; those results also revealed that fish can control body-generated vorticity, through body flexure and active manipulation by the caudal fin. Other researchers [25], using DPIV, approach the question of why some fishes are able to swim faster than others, from a hydrodynamic perspective (**Figure 2(d)**); they investigate the structure and strength of the 3D wake to determine how hydrodynamic forces varies on Black surfperch (*Embiotoca jacksoni*) and Bluegill sunfish (*Lepomis macrochirus*). Both species (similar in size) swim at low speed using pectoral fins exclusively and both species at high speed, switch to pectoral-caudal fin locomotion; the surfperch can swim twice fast. It was found that surfperch presented a pair of linked vortex rings for all velocities, while the sunfish for low speed, presented only one vortex ring per fin and a pair of linked vortex rings with one ring only partially complete and attached to the body, at maximum speed. One of the most striking aspects of fish diversity is the presence of multiple locomotor control surfaces playing hydrodynamic roles during steady swimming and unsteady maneuvering locomotion, as well as the vortex wake interactions among all fins, a subject to be fully understood in the future. The skin of fast-swimming sharks (mako sharks) [26] is composed by a tooth-like scales (denticles) that generated vortexes on the front edge of the skin, *i.e.*, eddies that essentially would help to pull the shark forward; this kind of skin composition is not found on slow-swimming sharks. Many researchers study this skin, by direct mimicking in its 3D shape or in a simplified grooved surface (riblets). Upon close examination of a dolphin's skin revealed micro dermal ridges that delay the transition to turbulent, by trap water molecules at the surface of the skin. Thus, the molecules of trapped water on the skin surface allows the animal to pass through the water more easily than if the same animal had a dry skin surface. The sailfish (that has V-shaped protrusions on skin) is known as fastest sea animal, reaching maximum speeds exceeding

110 km/h. His fin on the back which grows along the back can be spread and folded at will. Since sailfish is the fastest-swimming animal, researchers expected that sailfish's skin textures might produce skin-friction reduction; however, directly measures and numerical investigation showed increases or negligible reduction (~1%) on skin-friction. Yet, scientists advanced other explanations; the role of sailfish skin knowledge is to be confirmed.

5. Insect: A Biological Flight Machine and Their Wing's Kinematics

Every insect's wings when in motion are deformed by either the aerodynamic forces from the surrounding air flow, or by the inertial acceleration; the overall wing deformation is a combination of both and is in a continuously and constantly changing. The power product of the flight's muscles is transmitted to the wings which unlike an aircraft wings are neither streamlined nor smooth: the shape, corrugation and performance of the wings and the complex flapping motion during each stroke cycle will determine the ability of an animal to fulfil successfully every stunning maneuver. Each wingstroke cycle is typically divided into two translational phases: upstroke and downstroke; and two rotational phases: pronation and supination. In the forward-downstroke movement—main power stroke—the wing initiate the downward loop with a high angle of attack until the leading edge tilts downwards, where the wing momentarily becomes horizontal in the middle of the stroke, minimizing the angle of attack; stalling is prevented due to the fastest moving of the wing at this point. During the recovery stroke, when the wing moves upwards and backwards, the leading edge tips backwards. The wing is rotated again at the top of the recovery stroke, restoring the maximum angle of attack immediately before the next downstroke movement initiation. Every motion streamed to the wing lies in a composition of rotational, horizontal, vertical and torsional movements. Torsional angles changes on insect's wings can be produced by active control, via muscles force, or by passive control, via inertial aerodynamic forces. Insect's flight maneuverability is remarkable and by far, superior to every maneuverability of any man-made flying vehicle. Dickinson *et al*. [27], stated that the aerodynamic performance of insects results from an interaction of three distinct, yet, interactive flight mechanisms: delayed stall, meaning that the wing sweep through the air with large angle of attack, during the translational portions of the stroke; rotational lift, meaning an augment in angle of attack at the end of the stroke, providing extra lift; and wake capture, meaning that the wing will capture some energy, left behind on the air by the previous wingstroke, providing extra power. Dragonfly wings possess great stability and high load-bearing capacity during flapping flight, gliding and hovering, despite the fact that their mass is less than 2% of the insect's total mass; such wings (forewings—front wings; and hindwings—rear wings) are composed by a thin cuticular membrane, supported by a vein system (venation) [28]. This venation structure consists on a net of veins (of different sections) that forms rectangular frames at the leading edge and hexagons or polygons with more than four sides at the trailing edge, allowing the requirements for different wing zones bearing different loads. Adding to this, their wings are highly corrugated (more corrugated at first 1/4 at the leading edge), which increases significantly the stiffness and strength of the wings and results in a lightweight structure with very good aerodynamic performance. The flow induced by the motion of insect's wings is highly unsteady and vortical. The aerodynamics between flapping and gliding flight differ substantially in two important ways: in a gliding wing, the air tends to remain attached and flowing smoothly over the surface of any airfoil; by contrast, the air over a flapping wing tends to become entrained in a swirling vortex bound to the upper surface of the wing—separated flow. And whereas the attached flow over a gliding wing look approximately similar from one moment to next, the separate flow over a flapping wing varies constantly—unsteady flow. Nowadays it is widely accepted that the insects make an extensive use of unsteady separated flow mechanisms in order to generate far greater aerodynamic forces that for them, would be impossible to achieve with steady, or quasi-steady, attached flow. In fact, insect's generate enough force to keep themselves in the air, because they flap their wings at a very high angle of attack that creates a structure at the leading edge of the wing, (a tornado-like structure) called leading edge vortex (LEV—see **Figure 3**). Large LEV's are formed at the beginning of each half stroke and remains attached to the wing until the beginning of the next half stroke. It was found on some small insects, an unsteady inviscid high lift mechanism (*clap-and-fling*—see **Figure 4**), consisting on the use of interaction between wings, as they press each other together (like a "*clap*") at the extreme ends of the stroke, providing a total vertical flapping angle of ~180˚.

At the end of the "*clap*", leading edges began to separate as the trailing edge remains connected initially (V-shape at ~120˚); after that, the trailing edge separates as well ("*fling*"); such movement leads that air to rush into low pressure widening gap and produce high strength vortices of equal and opposite sign [29]. The current

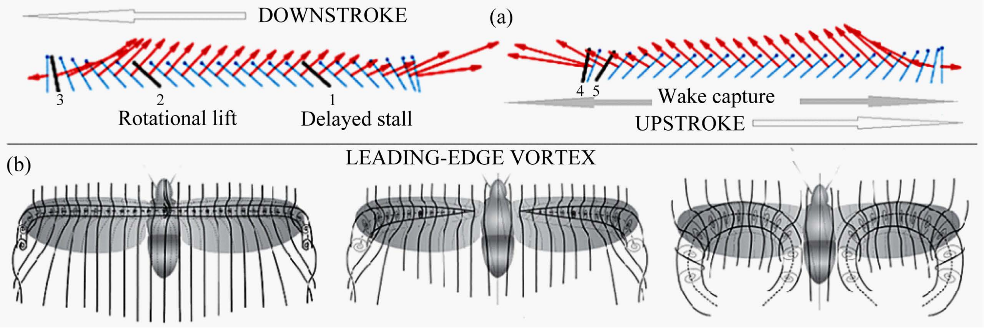

Figure 3. (a) Illustration of a complete insect wingstroke showing the delayed stall and rotational lift on the downstroke movement and the wake capture during all course of the upstroke; blue colour-wing position, with leading edge always on top; red colour-representing the total force [31]; (b) Illustration of 3 different leading-edge vortex: extends across thorax; attached at the base of the wing and horse-shoe-shaped vortex on both wings.

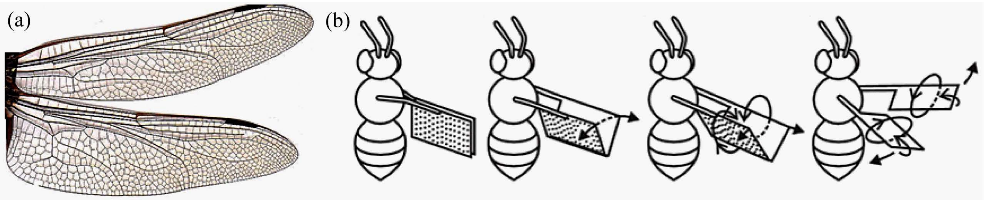

Figure 4. (a) Illustration of forewings and hind wings of a dragonfly and their venation structure as referred on [27] and also a pigmented cell known as pterostigma which mass is frequently greater than that of an equivalent area of adjacent wing and its inertia influences the movement of the whole wing movements. Without the pterostigma, the self-excitating vibrations would set in on the wings after a certain critical speed—pterostigma acts as an inertial regulator of wing pitch; (b) Illustration of the "*clap-and-fling*" flight mechanism: at a certain moment, the wings press together each other (clap); then wing separate as shown (V-shape), generating a low pressure zone between them.

state of the art of micro-CT scanners (X-ray Microtomography) is nowadays limited to large insect's wings [30]; since the resolution of micro-CT scanners is increasing every year, in near future, any insect wing could be successfully scanned. The main challenge for accurately digitizing the wings 3D architecture is minimizing the deformation due to drying of the wing needed to reduce scatter and noise in the scan due to evaporation. Researchers used this technology to scan a dragonfly "*Sympetrum vulgatum*" forewing and hindwings; they found that both vein and membrane thickness increases from tip to root on both wings, which allows the wing to effectively bear both inertial and aerodynamic loads. On their model, they discover that the inertial loads along the wingspan were approximately 1.5 to 3 times higher than the aerodynamic loads—wings deformation were dominated by inertial loads. Based on computations, they also found that wing deformation was smaller during the downstroke, due to structural asymmetry. By the analyses on the work on several researchers, In fact generically, both inertial and aerodynamic force can be the primary cause of wing deformation: in contrast with above statement, and referring also to dragonfly's natural wings, a study concluded that their deformation was mainly due to the aerodynamic forces. Insects have no active control over the wing configuration during flight. The architecture of the wing and the material properties of its element determine how the wing changes their shape in response momentarily to external forces changing, since the wing movement is very complex. It is nowadays a great challenge to researchers, how to build a model with similar properties; of course, another challenge is how to incorporate the wing flexibility into the theoretical model predicting the aerodynamic force during insect flight—both, remains an ongoing challenge to the researchers [32]. As previously referred, leading-edge vortex is the main flight mechanism that allows insects to be able to fly; studies on the unsteady aerodynamics on the flapping wing of a *Manduca sexta* hawkmoth robotic model (while hovering) were made by the use of computational fluid dynamic (CFD) modelling [33]; CFD computations revealed a large leading-edge vortex (LEV1) presence during most of the downstroke movement (from the base at ~60/75% of the wing length); as the wing moves towards horizontal position, this structure becomes larger spiralling vortex with strong axial flow at the core, towards the wing tip. Immediately after the middle of the dowsntroke, the LEV breaks down at 75% of the wing length, creating this, a second LEV (LEV2—also revealing a spiral axual flow towards the wing base) between the wing tip and the broken-down position of the first LEV. At the initial supination rotation, LEV2 is pushed off the leading edge due to wing deceleration and the breakdown point of LEV1 moves into half of wing length. During the upstroke a very-small leading-edge vortex (quite 2D structure) appeared at the wing tip and by the time the wing reaches the middle position, this structure extends from wing tip to the wing base. After the upstroke's middle course, the LEV grows rapidly (comparable in size with the dowstroke LEV1) and hence enlarges the negative pressure region. At the later part of downstroke, the LEV breaks don at ~60/70% if the wing length without shedding the tip vortex. During the pronation, the upstroke LEV remained attached to the leading edge of the lower wing surface and a trailing-edge vortex (TEV) was also detected (larger than LEV, lies below it and run from the base to the tip), probably due to wing rotation. Lentink & Dickinson [34] suggested that LEV could be an efficient high-lift mechanism for small and big hovering insects; this suggestion is reenforcing the idea that insect while hovering, more easily might capture the energy left behind in air, by the previous stroke; even more, the insects with four separated wings (part of them as two pairs coupling wings) might benefit their rear pair on the work of forewing's wake flow. A challenge on build insect's wing models approaching the natural wings morphology was made by Tanaka & Wood [35]. They described the fabrication of an artificial insect (hoverfly) wing with a rich set of topological features by micro molding a thermosetting resin; the venation system diameter varied between 50 - 125 μm heights and the corrugation of the wing measured 100 μm. Both solid veins and membrane were simultaneously formed and integrated by a single molding process, by the use of a layered laser ablation technique; each 3D mold were created with 5 μm resolution in height. The replicated wing matched at-scale high precision surface profiles of the natural one, thus enabling parametric experiments of the functional morphology of insect wings. Authors referred that stiffness measured along the natural and model wings on identical values of magnitude. However, nature had adapted insects with wings were stiffness varies ad varies the location region on the wings. Later, on another investigation [36] on the subject of flexural and torsional wing flexibility, they were able to create a rigid wing model (hoverfly) that could produce more lift than the natural one's, thus, in prejudice of maneuverability, a requirement that insects had at their disposal (at their will), at almost 350 million years: the experience to fly in the skies of the Earth. After filming a beetle tethered flight [37] with a high-speed camera, researchers build a model of wing system of identical size of natural wings, on a way to follow the natural performance of: flapping frequency, stroke plane, wing tip path, wing rotation angles and flapping angles; however, their experience demonstrated to them that flapping frequency and wing rotation need an improvement to satisfy the natural mimic, since the positive vertical force achieved was only ~1/5 of the total weight of the system. From all bibliographic revision on birds, bats and insects, all researchers invoked that those flying animals may benefit aerodynamically from the flexibility of their wings—a general idea stating that temporal wing deformation is the basis of force generation. From the design aspect, flexibility may benefit MAVs as well, from several points of view: aerodynamically and lightness of structures. Since insect's flight maneuverability far higher superior to every maneuverability achieved by any man-made flying vehicle, thus, Barata *et al.* [38], made an extensive comparative bibliographyc research on the wings motion patterns on several types of insects on resemblant flights, regarding the expoliting of their in-flight basic principles for the acquired performance. They found that the same insect uses their wings in very differently manners, depending, thus, on the maneuver they intend to carry. Every single movement of their wings generates lift (downstroke or upstroke) and the time rate downstroke/upstroke could easily vary at their will. Some of them possess the ability to use the wings in independent ways (differences on wing stroke, wings with different torsions at the same instant, or even one wing used as aerodynamic brake). Despite the flight mechanisms used by insects are not yet fully understood by humans, their replication for use in MAVs will be even more far from being achieved.

6. Conclusion

The current investigation is focused on the mechanisms involved with natural locomotion (thrust and/or lift). Biological systems with interesting applications to Micro Air-Vehicles (MAVs) are generally inspired on flying insects or birds; however, similarly to the aerodynamics of flight, powered swimming requires animals to overcome drag by producing thrust. Commonalities between natural flying and swimming are analyzed together with flow control issues. As it was shown by several researchers on this bibliography work review, the perception of flight performances held by insects and swimming performances held by fishes are not completely understood. All control surfaces present on living aquatic and flying animals (feet, fins, flippers, or wings) are not designed by nature as of rigid materials; instead, they are elastic materials. Insect's wings are morphological wonder (elastic material: every wing motion is a sum of horizontal, vertical and torsional movement), however, what really enables the wings to make enough force for the animal to stay in the air, is the way insects flap them: at a very high angle of attack, creating a structure at the leading edge of the wing, (tornado-like structure) called leading-edge vortex. Researchers investigated dimensionless numbers to study swimming and flight, and their findings were disappointing since it became clear that different points of view exist in the biomechanics field on how to best define and use. So, successful biology-inspired or biomimetic concepts will depend on the understanding of the natural mechanisms especially when they do not agree with the present engineering design principles. An additional difficulty (and a very important one) is the fact that state of art on elastic materials with identical or similar elastic properties of natural insect's wing, does not exist yet.

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