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BIOLOGICAL INSPIRED PROPULSION OF MICRO-AIR VEHICLES

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Summary: *This paper presents a review on aerodynamic and propulsion mechanisms involved with natural locomotion (propulsion or propulsion and lift). A discussion of typical flight stages highlights the behavioural capacitance and ability of living organisms in locomotion that provide inspiration on their manoeuvrability and agile flight for the design and control of MAVs and NAVs.*

1 INTRODUCTION

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 [1]. 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 (150mm) flying vehicles to operate in D^3 – dull, dirty and dangerous – environments [2]. More recently DARPA launched a Nano Air Vehicle (NAV) program with the objective of developing and demonstrating small (<100mm) lightweight air vehicles (<10g) with the potential to perform indoor and outdoor missions [3]. All requirements of low-altitude, long flight duration at low speeds (up to 100km/h), small wing spans and masses, together with demanding capabilities of take-off, climb, loiter, hover, manoeuvre, 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 [4]. Nevertheless, biomimetic engineered devices are still far from the living organisms and more research is needed [5].

There is a general agreement that an unsteady dynamics approach is required to capture the physical phenomena at this scale [6]. Additionally, propulsion and lift should not be considered independently. Flapping wing systems appeared in animals such as insects, birds, and fishes, which are known to exhibit remarkable aerodynamic and propulsive efficiencies. So, there have been several experimental and numerical studies of the bio-mimetic propulsive flapping[7,8]. 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 aerofoil configuration has been considered far less and the published work is not always in agreement. For example, the results of [9-11] show that thick aerofoils can improve plunging aerofoil performance, whereas [12-13] suggest than thin aerofoils perform better, and the inviscid analysis of [14] concludes no influence of aerofoil thickness on plunging aerofoil 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 [15-16]. Additionally, [17] reported 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-wake interactions, and the corresponding propulsive forces with their fins and wings. [18] 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.

This paper will focus on mechanisms involved with natural locomotion (propulsion or propulsion and lift). Commonalities between natural flying and swimming are analysed together with flow control issues. The study has been driven by the behavioural capacitance and ability of living organisms in locomotion that provided inspiration on their manoeuvrability and agile flight, for the design and control of man-made MAVs and NAVs.

2 BIOFLUIDDYNAMIC MODELLING OF ANIMAL SWIMMING AND FLIGHT

The fluid dynamics of many swimming and flying animals involves the generation and shedding of vortices into the wake. These vortices may interact strongly by merging or tearing each other apart changing the wake topology abruptly. A two dimensional flapping foil is a simplified model of animal wings, fins or tails. Consequently, relatively small changes in the kinematics of a flapping foil can change the topology of the vortex wake drastically.

2.1 Aerodynamic and propulsion mechanisms

Many fish depend primarily on their tail beat for propulsion. In the case of flying animals, the wings are flexible structures that constantly changing their shapes while pivoting and rotating about a movable hinge and their kinematics can be defined as a result of several parameters: wingbeat frequency, stroke plane angle, stroke amplitude, mid-stroke angle, stroke plane deviation angle, wing rotation and wing deformation. Most of the insects in both normal hovering and forward flight revealed the ability to reverse the upper and lower surfaces of the wings about their longitudinal axis every half-stroke, leading to a high lift and low drag production (Figure 1). The centre of rotation of the wing´s insects tends to be very close to the leading edge and therefore anterior to the aerodynamic centre of pressure. Therefore, aerodynamic forces tend to twist naturally the

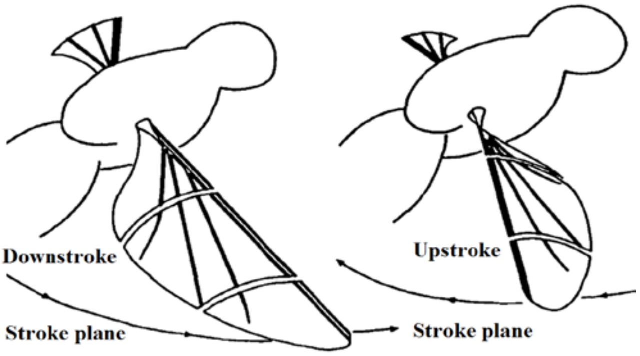

Figure 1: Reversal of torsion and camber on the wings of a typical insect between half-strokes [19].

wing in the most efficient way [19]. 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 aerofoil, while the air over a flapping wing become entrained in a swirling vortex bound to the upper surface of the wing. Whereas the attached flow over a gliding wing looks steady, the separated flow over a flapping wing varies continuously. Insects make an extensive use of unsteady separated flow mechanisms in order to generate far greater aerodynamic forces that would be impossible to achieve with steady attached flow. The flow over a gliding wing remain attached to the wing´s surface (at low angles of attack – and becomes stalled at high angles of attack), whereas the flow over a flapping wing typically separates at the leading edge and becomes entrained within a swirling vortex constantly present on the top of the wing (Figure 2). This indicates that such a separated flow mechanism is the most important for the insect´s flight. The presence of the leading-edge vortices on top of the wings results in a local reduction in pressure, which causes an upwards-acting suction force known as vortex lift. In the available data of insect´s flow visualization, this aerodynamic mechanism was observed in *Lepidoptera*, *Diptera* and *Odonata*, although it can be avoided by modifying the angle of attack (*Orthoptera* and *Odonata*). Smoke visualizations of free-flying bumblebees indicate the presence of independent leading-edge vortices on the root of each wing pair and its influence on the downwash distribution [20].

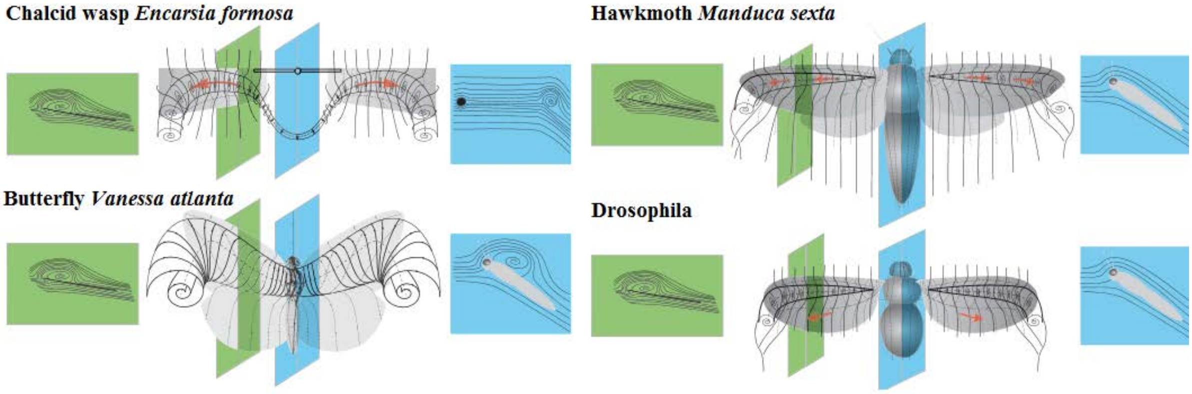

Figure 2: Schematic drawings of three class flapping wings with leading-edge vortices; Class I – Chalcid wasp; Class II – Butterfly; and Class III – Hawkmoth *Manduca sexta* and Drosophila [21].

The aerodynamic forces acting on a wing increase as the angle of attack increases. So, the expected effect of rotating the wing leading-edge upwards, as in supination, is to increase the aerodynamic forces. Rotational lift is created when the insect rotates the angle of attack of its wings, creating vortices, and at is completion, such manoeuvre result in a powerful force propelling the insect forward. By rotating a wing leading-edge upwards delays the onset of stall and thereby extends the production of useful aerodynamics lift to higher angles of attack. This unsteady effect is known as the Kramer effect and may be responsible for the transient lift enhancement observed during the wing rotation in an insect flight.

When an object moves quickly through a fluid, vortices are formed. In general these vortices (vortice wake - turbulence left behind the object) represent lost energy, as it takes energy to make them. Most flying insects push off of the vortices that they create, thus recapturing some of the wasted energy and adding power to each of their wingstrokes. These interactions have a particular significance in hovering flight, due to the possibility of a wing re-encountering the wake that it left behind on the previous stroke. These wing-wake interactions are also very important in functionally four-winged insects, where the hindwings operates in the wake of the forewing, and may reduce power consumption as in dragonflies. Both rotational and translational mechanisms may explain the variety of wing´s patterns displayed by each different species of flying insects, essentially due to the fact that all insects enhanced aerodynamic performances results from the interaction of such three distinct yet interactive aerodynamic mechanisms: delay stall, rotational lift and wake capture (Figure 3).

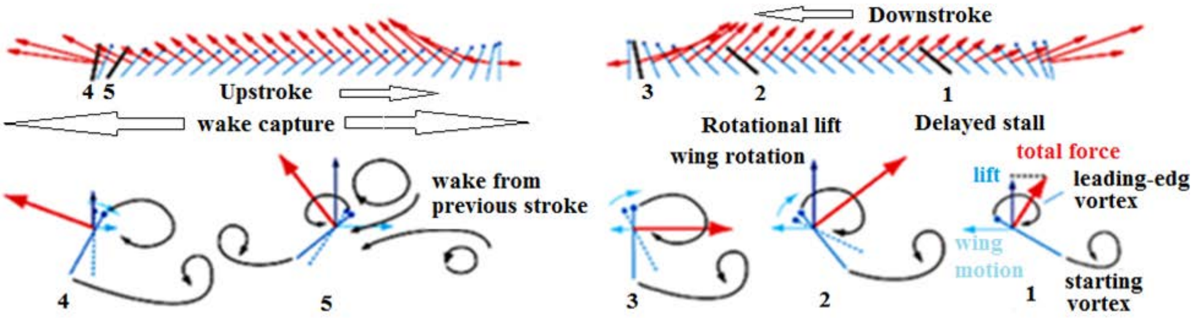

Figure 3: Schematic drawings of the aerodynamic mechanisms of: rotational lift (2), delay stall (1) and wake capture (5).

Another important mechanism is the clap and fling or wing-wing interaction/Weis-Fogh mechanism (Figure 4). This is used by some flying animals to quick-start lift on the wings. Both wings are clapped together above the animal on the upstroke, and then peeled apart (downstroke). The clap mechanism consists on both wings clapping together above the animal on the upstroke. Prior to the dorsal stroke reversal, as the wings come together and join, they carry with them leading edge vortices (LEV) and trailing edge vortices (TEV) and wakes which attenuate each other due to their mutually opposite sense. And as they clap together, they squeeze out a jet of air between them, which the insects can use to augment thrust. Some insects may enhance their manoeuvrability by redirecting this jet of air [22, 23]. The fling mechanism starts immediately when the wings peeled apart forcing the vorticity on the wings. Air flows around the leading edge of each wing creating a bound vortex on each wing acting as the starting vortex for the opposite wing which allows a rapid build-up of circulation as well as a handy low-pressure zone above their body (expelling air from between

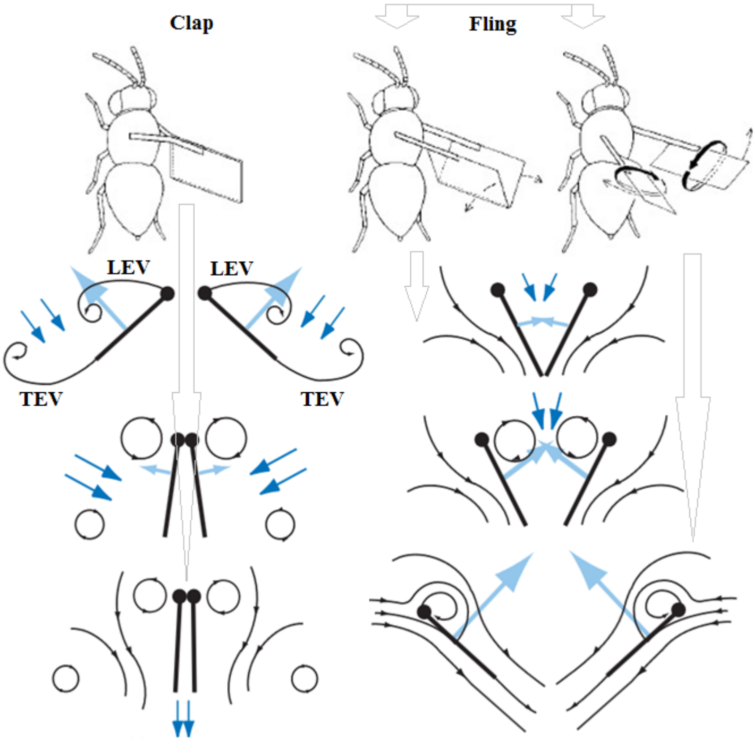

Figure 4: Scheme of the clap and fling mechanism [22].

them), with the consequent increase in total lift production (when the wings then separate, air is quickly drawn in to fill the void). As the wings are flung apart, the lift is immediately generated because the air is already moving in the correct way. The aerodynamics of the clap and fling are understood as an example of wing-wing interaction. This kind of mechanism is best known from the chalcid wasp *Encarsia* (Hymenoptera) which has a wingspan of ~1.3 mm and a wingbeat frequency of ~400 Hz. Lehmann *et al*, employed a dynamically scaled mechanical model of the small fruit fly *Drosophila melanogaster* (100 < Re < 200) and by the use of a detailed digital particle image velocimetry (DPIV), they investigated the force enhancement due to contralateral wing interactions during the clap-and-fling movement. The insects clap their wings together at the end of each upstroke and fling them apart at the beginning of each downstroke [24, 25]. According to [26], the clap and fling motion has also been reported by several authors in the greenhouse whitefly *Trialeurodes vaporariorum*, in the *Thrips physapus*, in the wasps *Muscidifurax raptor* and the jewel wasp *Nasonia vitripennis*. Fling has also been observed in a few medium and larger insects such as butterflies and moths and the tethered flight of *Drosophila melanogaster* (rarely observed in free flights). The clap and fling mechanism has a variation mechanism - the clap and peel: instead of flinging apart more rigidly the wings peel apart due to fluid-structure interaction between the air and the flexible membrane wings: a peel mechanism with flexible wings might actually serve to augment lift forces relative to the rigid-fling case. The correlations between wingbeat frequency - wing loading - body mass indicate a dependency on several subjects: in general, insects with high wing loading have a high wingbeat frequency and insects with low wing load have a low wingbeat frequency; for very small insects (weight <0.03g) such correlation is not verified: very low body mass distributed by the wing surface, gives exceptionally low wing loads. Farther, some minute species solve their extra lift generation by employing the clap and fling mechanism, thus reducing the need of higher wingbeats frequency. Additionally, very small insects accomplish their flights by relying on the ability to use wind currents passively. Also, small insects may have reduced settling velocities because they possess high drag coefficients [27].

2.2 Analysis of typical flight stages

Hovering flight is the most power-demanding type of locomotion in animals and is far more expensive than ordinary flapping flight because, relative to the undisturbed air, the body has no accumulated kinetic energy. Ref. [28] found that while in hovering flight, during the upwards movement of the insect´s wings, the gravitational force causes the insect to drop and during the downward, such movement produces an upwards force that restore the

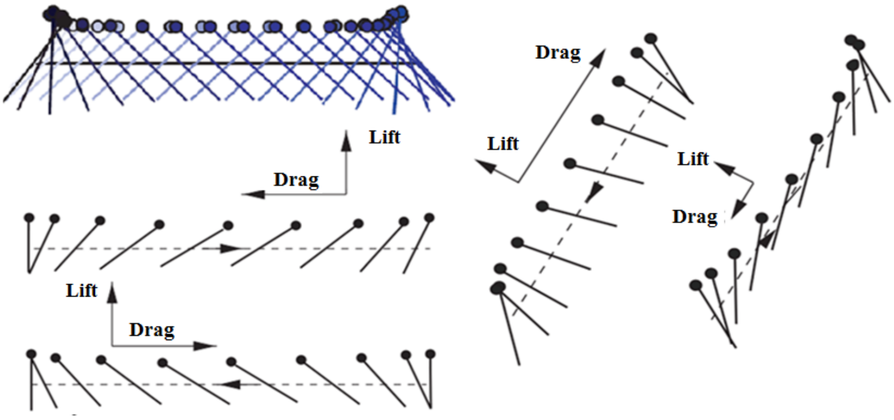

Figure 5: Left; Normal stroke-plane hovering, with the wings trajectory in the horizontal plane, and right; Inclined stroke-plane hovering, in the case of the dragonflies the wings trajectory is in 60º in relation to the horizontal plane.

insect to its previous original position revealing a vertical position oscillation generated by the wingbeat frequency of the insect. High-speed video recorded [29] of free hovering flight of the dragonfly *Aeschna juncea* has shown that the animal body was held almost horizontal (~10º head-up) with both fore and hindwings beating at a frequency ~36-40 Hz in two almost parallel strokes planes tilted 60º relative to the horizontal. Other studies [30] revealed that the dragonflies hovering flight were performed with a 180º fore to hindwings difference phase (out of phase) and angles ranging within 54-100º for forward flight and no difference phase (0º, in-phase) for the accelerating or to perform aggressive manoeuvres. Dragonflies' often [31] take-off with in-phase flapping (0º) after what the forewings slows and the hindwings speeds up their beat for the normal antiphase (180º) pattern in one or two beats. During the flight they occasionally shift for in-phase flapping by reverting the same process (the transition is made in one wingbeat). And rarely flapped in phase for more than 5 or 6 wingbeats at a time, whether as on free or tethered flight. This pattern is used in situations that call for greater than normal force production: take-off, yaw turns and to reverse direction. While most flying insect's use a horizontal stroke plane, dragonflies are approximately 60º from the horizontal. In fact, several studies confirmed that dragonflies and hoverflies use an inclined stroke plane for their hovering flights and these animals can remain hovering motionless in the air for a long time, a reputation that they compete as best flying hoverers. The stroke amplitude of hoverflies in flight stage range from 65 to 85º. The downstroke angle of attack (~50º) is much larger than the upstroke (~20º), unlike normal-hovering insects, whose downstroke and upstroke angles of attack are not very different. A mathematical model [32] to analyse the flight of bumblebees at different speeds indicate that their flight is unstable while hovering and fly slowly and becomes neutral or weakly stable at medium and high flight speeds. This instability is observed in both stage flights is mainly caused by a sideways wind made by the movement of the wings - a "positive roll moment". As the bee flies faster, the wings bend towards the back of the body, reducing the effect of the sideways wind and increasing the stability of its flight. Ref. [33], revealed that honeybees can hover at a relatively low strokes amplitude (~90º) and high wingbeat frequency (~230 Hz), producing multiple force peaks during each wingbeat. When the honeybees were moved from normal air (1.21 kg/m^3) to heliox (0.41 kg/m^3) they raised the stroke amplitude (more ~50 degrees) while maintaining constant the wingbeat frequency. Under hover flight conditions [34] and [35] showed numerically that left and right wings interaction (bees and flies) was negligible except during the "clap and fling" motion while [35] and [36] observed that the wing/body interaction was also negligibly small (less than 2 %). Ristroph *et al* [37], found that when the fruit flies are hovering or flying slowly, the average angle of their wings is near-vertical, with the wing tilted in opposite directions on the forward and backwards strokes. Inevitably, the drag forces of the air on the wing also push the insect back and forth, but the two cancel each other out. To fly faster, the fruit flies tilted their wings closer to the horizontal on the forward stroke to slice more cleanly through the air and then closer to the vertical on the backward stroke to maximize drag - paddling through the air. Hovering with extra weight - A well-laden honeybee can carry pollen and nectar as much as 80% of its own body weight. According to [38], pollen foragers had hovering metabolic rates approximately 10% higher than nectar foragers, regardless of the amount of load carried. They found that honeybee foragers are able to carry significant loads without changing wingbeat frequency, stroke amplitude or inclination of stroke plane. Ref. [39] identified a normal hovering flight displayed by a *Drosophila* fruit fly performed on two different wing motion patterns: symmetrical and unsymmetrical (Figure 6). Additionally, the middle and outer wing-sections produce more than 95 % of the lift and drag. Flapping wings creates high force transients during the stroke cycle; even the slightest variation in the wing motion can rapidly alter the orientation of Drosophila fly and may lead to a hovering flight immediately followed by saccadic turning manoeuvres, where the body of the animal may reach 2,000º s^{-1} within a few wing beats. High-speed videography of [40] of individual *Manduca sexta* hawkmoths (*Lepidoptera*) in free flight over a range of speeds from hovering to 5ms^{-1} revealed that the stroke-plane angle on several individuals ranges between 10-30º and the body angle ranges between 30-40º, both relative to the horizontal plane. The stroke-plane increases as speed increases and values of 50-60º at 5ms^{-1} were found while the body angle decreases as speed increases and indicates values of 15-20 at 5ms^{-1}. In hovering flight, the trend for stroke amplitude is about 115-120º for the inner section of the wings; the outer sections peaked at over 150º (angle of more than 20º between inner/outer section of the wings). The wing pronated rapidly at the top of the stroke and a relatively sharp trough of rotation angle was reached early in the downstroke with the outer section at an angle of ~35-45º and the inner section at approximately ~5-10º steeper. Significant twisting along the wing´s length reappeared in translations phases as the inner section started to rotate in advance of the outer section. The mean angular velocities during the stroke reversals were respectively high as 10,000º s^{-1} for the outer section and more than 5,000º s^{-1} for the inner sections of the wings. The results confirmed a decrease in the stroke amplitude angle with the increasing of speed to values within $0 \le ms^{-1} \le 3$, suggesting that the amplitude is controlled through the minimum wing position. The separation between wing couples during pronation was held constant, and the supination position became less ventral with increased flight speed. The results revealed also an asymmetry between the duration of the two half-strokes with the downstroke/upstroke ratio varying from 1.06 to 2.00 with a mean value of 1.42. These values were particularly high, but the ratio on insects with asynchronous muscles generally tends to ratio values superior to 1.00. The wingbeat frequencies fell within the narrow range of 24.8≤Hz≤26.5 and decreased with the slightly increase of speed; the relationship between speed/wingbeat frequency figures a U-shape graphic, with the lowest frequencies at intermediate speeds. Ref. [41] investigated the hovering flight on butterflies

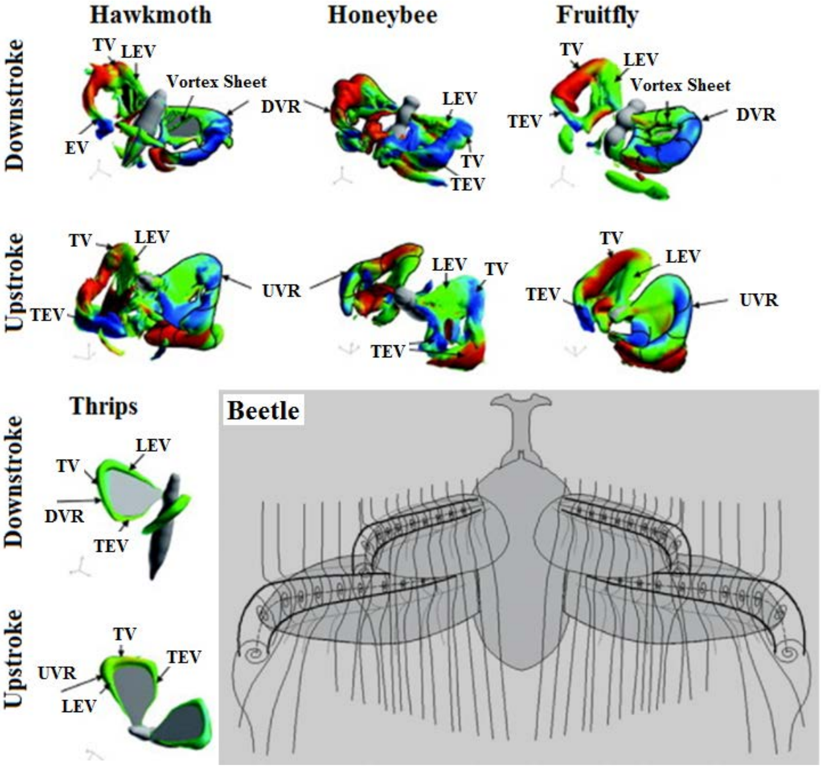

Figure 6: Different patterns of leading-edge vortices on hovering flight conditions: hawkmoth, honeybee, fruit fly and thrips – by integrated numerical framework consisting on the realistic wing-body morphology [44]; and a beetle – by visualization [43].

(*Lepidoptera*), and found a pattern in most species with the body inclined 15º to the horizontal. Normal hovering was observed in many flights and inclined stroke-plane was also observed exceptionally. The stroke amplitude varied in a range within $24º\leq\Phi\leq90º$ with a wingbeat frequency within $5.1\leq Hz\leq21$ and mean angular velocity up to 145 rads^{-1} obtained by *Papilio rumanzovia*. The upstroke/downstroke relationship indicates an increasing on values, when compared with obtained results for another flight stages and revealed values of $0.8\leq U/D\leq0.92$. Wing uncoupling during hovering flight [42] was recorded on *Parides neophilus*, where hindwings were held open and stationary and the aerodynamic force production was achieved entirely by means of forewing strokes at high frequencies, with the angular extent of motion of the forewings being ~90-100º. During hovering flight, the wings of the chalcid wasp *Encarsia formosa* [39] present a normal hovering pattern moving horizontally with the body kept almost in vertical). Their wingstroke indicates three unusual phases: the clap, the fling and the flip; in the flip, which is a supination at the beginning of the morphological upstroke, the wings are rapidly twisted through about 180º. Flow visualization on Rhinoceros Beetle (*Trypoxylus dichotomus*) [43] during the hovering flight indicate the use of a reverse clap and fling mechanism, where the hindwings touch together at the end of the downstroke. During the flapping motion, both elytra and hindwings flap with the same frequency (37-40 Hz) however with very different stroke angles (elytra: 34º-38º; hindwings 160º-180º). The non-dimensional upstroke/downstroke ratio indicates ~1. The elytron generated relatively small vertical or horizontal forces, indicating no significant contribution to the aerodynamic force for hovering maintenance. Leading-edge vortices appear on the hovering flight of the beetle on both elytron and hindwings, with its size constantly enlarged from the beginning to the end of the downstroke movement; the observed LEV on elytron may consequently produce a lift force in forward flight; such wings may have not the exclusive purpose of protecting the hindwings. A recent numerical research on Reynolds effects on several realistic wing-body morphology insects hovering aerodynamics - hawkmoth, honeybee, fruit fly and thrips - indicate an overview of scaling effects on vortex dynamics and wake structures. The hawkmoth model is based on the experimental data of an hovering flight of *Manduca sexta*, with a body angle of 39.8º, stroke angle of 15º relative to the horizontal, amplitude stroke of 114.6º and wingbeat frequency of 26.1 Hz. The honeybee model is based on the experimental data of an hovering flight of *Apis mellifera*, with a body angle of 45.0º, stroke angle of 0º relative to the horizontal, amplitude stroke of 90.5º and wingbeat frequency of 229.8. The fruit fly model is based on the experimental data of an hovering flight of *Drosophila melanogaster*, with a body angle of 45.0º, stroke angle of 0º relative to the horizontal, amplitude stroke of 139.8º and wingbeat frequency of 200 Hz. The thrips wing-body model is based *Franklinella intonsa*, and all of their kinematics observed were similar to the flapping of a small insect, like fruit fly: body angle of 45.0º, stroke angle of 0º relative to the horizontal, amplitude stroke of 139.8º and wingbeat frequency of 200 Hz – Re ~12 (thrips hovering flight ↔ $5\leq Re\leq20$). All models are based on rigid wings. The results revealed how the leading-edge vortices (LEV) is related to the trailing-edge vortices (TEV) and the tip vortex (TV) as well as to a downstroke and upstroke vortex ring (DVR, UVR) and pointed to the importance of the vortex ring in stabilizing the LEV and hence in enhancing the force-generation [44]. Transitions from hovering to slow speed flight indicates [45] on few changes: the horizontal forward or backward flight is achieved with a change in the mean stroke angle; the vertical climb or decent is achieved with stroke a change amplitude or an equal change in the down- and upstroke angles of attack, *i.e.*, a proper combination of mean stroke angle and stroke amplitude controls can give a flight of any (small) speed in any desired direction.

Some insects are capable of hover for a long time and suddenly change their direction, elaborate flight manoeuvres that outperform other flying animals and any man-made flying vehicles. Observations of [22] on turns sequences in dragonflies revealed two distinct types of turns, namely the conventional (accomplished with roll - banking, analogous to a turning airplane) and the yaw (accomplished without roll). Yaw turns were extremely fast in free flight - 90º in 2 wingbeats and 180º in less than 3 wingbeats; in tethered flight - 90º in 4-6 strokes. In the conventional turn in order to roll into a bank, dragonflies produce unbalanced forces on one their sides, *i.e.*, left-right asymmetries in the wing stroke angle and consequently on the angle of attack (changing the amount of one side lift vector that produces the turn - probably most useful during fast forward flight). The sequences of conventional turns show that one or both pairs of wings are left-right asymmetries in the stroke angle, with the lower vector causing the turn. The stroke angle was found to be also asymmetric with the lower amplitude on the wings inside of the turn (inner wings) and in several cases with a clearly higher angle verified on the wings outsider the turn (outer wings). Dragonflies may change the inner and/or the outer wings on one or both sides, as well as the fore- and

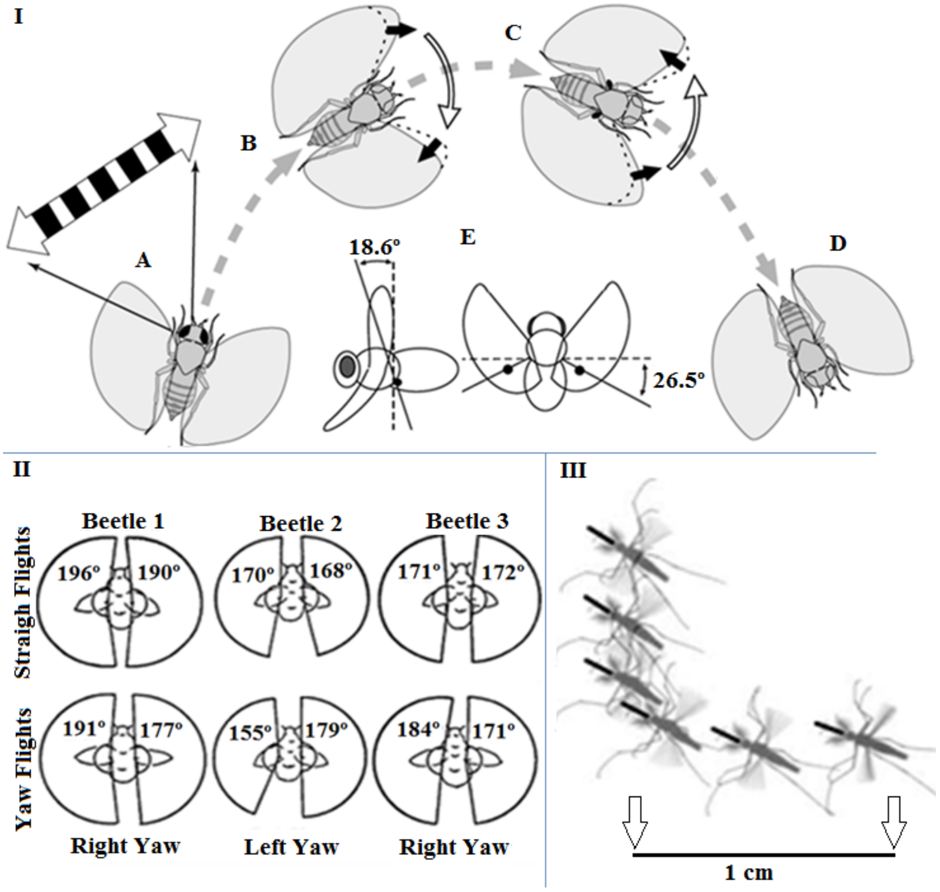

Figure 7: I) Saccade summary [37]: A) The visual expansion triggers the saccade; B) the insect produce small changes wingstroke changes; C) the halteres detect rotation and triggers counter-turn; D) the fly continues on new heading. - E) Detail of the angular orientation of the halteres stroke plane; II) Comparison of the horizontal amplitude wingstrokes on the straight flights and on the yawing turns on beetles [35]; and III) Snapshots of a mosquito turning maneuver at 30 ms intervals ~25 wingbeats; a rapid change in flight direction while the insect’s heading evolves much more slowly and does not change very much [36].

hindwings strokes with each one of the all four wings at a different stroke angle. Once the desired bank angle is established, the animal returns to its previous normal stroke pattern. The yaw kind of turning manoeuvre is initiated with forewings having similar amplitude and the fore- and hindwings not in phase, but reaching the in-phase almost immediately. At that time, the forewings begins to diverge their amplitudes: the outer wing reaching much larger amplitudes, presenting extreme swings of the forewings angle of attack, caused by the outer wing peak during the downstroke and the inner wing higher on the upstroke with a peak at the top of one stroke. Initially, the inner hindwings presented a higher vertical amplitude component that became similar when the fore- and hindwings reached the in-phase. Subsequently, the hindwings angles of attack increased during the turn and have no consistent patterns of asymmetry. As result, the first stroke revealed a strong asymmetry in horizontal stroke angle and yaw the insect ~10º. During the second upstroke the outer wing moved with much higher horizontal amplitude and the insect yawed its body ~15º. Dragonflies may also turn while gliding by the exclusive change on the angle of attack. Locusts could use differential changes in wing profile (camber) as a way to produce unbalanced lift and thus initiate a turn. Fruit flies can often fly via straight sequences of movement interspersed by rapid turns called *saccades* (also known as collision avoidance manoeuvres), characterized by a rapid rotation of the body about the yaw axis (*sharp and right angles turns).* The fly starts the *saccade* with a path velocity (~0.19 ms) and slows down to (~0.08 ms) as it changes heading, and then accelerates forward at the end of the turn. The *saccade* is generated by two specific and remarkably subtle changes in wing motion strongly correlated with the yaw torque: a backward tilt of the stroke plane, that elevates flight force during the upstroke by increasing the aerodynamic angle of attack; and an increase in stroke amplitude that further augments force by elevating wing velocity, i.e. by inducing differences between the amplitude of the left and right wings of about 5º and shifting the stroke plane by about 2º. At the onset of a *saccade* the outside wing undergo these changes, thereby creating torque to rotate the body at the start of the turn. After about ~20 ms the inside wing exhibits similar changes, thereby generating counter-torque to terminate the *saccade*. A fly can change direction by 90º in less than 50 ms [46]. The maximal angular velocity [47] during a *saccade* turning is independent of the forward velocity of the fruit fly and is approximately 1,600º s^{-1}, while their continuous smoothly turns are well below 1,000º s^{-1}. Such profile depends critically on at least three factors: time course of yaw torque, the moments of body inertia and the frictional damping on body and wing. *Drosophila* can perform a saccade during a vertical ascent. By increasing and decreasing the amount of haltere-mediated feedback decreases and increases *saccade* amplitude respectively [48]. Halteres most important roles is to provide rapid feedback to wing-steering muscles to stabilize aerodynamic force moments and also to stabilize the head during flight, thus acting as a balancing and guiding system, helping these insects to perform their fast manoeuvres. Beyond *saccades* fast turns [49], the repertoire of flies indicate also other kind of turn: the horse-fly *Hybomitra hinei* have been recorded using a modified form of Immelmann turn (half-loop followed by half-roll) in rapid reversals of flight direction. Despite the lack of halteres, the flight behaviour of hoverflies repertoire (*Eristalis tenax*: mass ~100/125 mg) and honeybees (*Apis mellifera*, worker, mass ~90/100 mg) includes also saccades. Independently of vertical motion, the hoverfly is able to fly sideways and backwards and can perform saccadic-like turns. Its head starts to perform the saccade ~10 ms later than the thorax and ends earlier and between the saccades typical interval (~200-300 ms) head and thorax are held stable with the head following the thorax motion. Honeybees can also perform sideways and backwards flights with intersected hovering periods lasting ~200 ms once or twice a second (between 220 to 500 ms and 1,540 to 1,760). They can also perform U-turns with no truly saccadic-like behaviour: the head shows saccade-like motion in the yaw direction every ~200 ms [50]. Stroboscopic photographs of tethered beetles executing yaw directional change revealed that such manoeuvres were mainly achieved by a unilateral increase or decrease of the horizontal amplitude of the wingstrokes [51]. Free flight of the "*Aedes aegypti*" mosquito reached a wingbeat frequency of ~850 Hz, with an unusual short and quick wingstrokes, subtending just 45º with their wings on each half stroke, compared with the -120º for the fruit fly [52]. A frequently used pattern of flight on these turns revealed an unaligned body orientation related to the flight direction, exposing that sideways acceleration plays an important role on part of their flight repertoire - mosquito flight direction changes more frequently and much more quickly than does body heading. These turning manoeuvres, in which the flight direction of the insect changes by 50º up to 200º, involve a combination of deceleration along the direction aligned with the body axis and acceleration in a sideways direction. A mosquito can fly continuously for up to twenty-four hours and are known to travel 150 km or more in nature [53].

Some gliding insects revealed three kinds of flight: on the free gliding, an insect simply stops stroking its wings and glides slowly down for a few seconds; on the updraft gliding at hill crests, the insect adjusts its wing positioning to float in the air without the need to beat its wings; and gliding in towed females, where a female in the wheel position holds her wings out and glides while the male provides the motive force. Detailed investigations [54-56] have been made for the dragonfly remarkable gliding capability. Dragonflies species have very different wings and in spite of this, when they are tested in similar conditions (Re = 7,000; angle of attack 5º) the results are similar in flow patterns and vortex trains generation process. The corrugation wings structures and cruciform configuration allows the air circulation in the cavities between pleats creating areas of very low drag that aid the lift-generating airflow across the wing (Figure 8). Such corrugated wings during acceleration do not change the form of the outer flow and revealed good stability in unsteady wind conditions, providing superior flying characteristics for MAVs fixed wings in low Re flight, enabling a continued stable flight at low Re. In addition, dragonfly configuration has

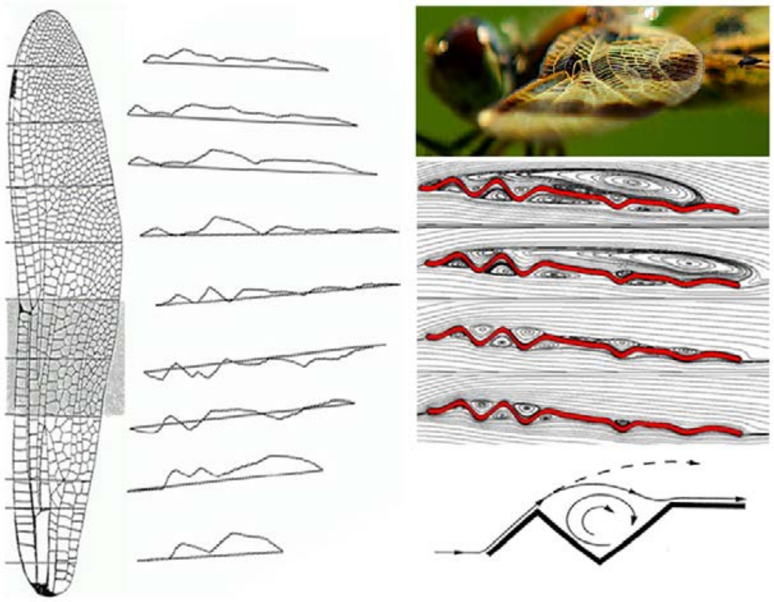

Figure 8: Left: Dragonfly wing and several cross-sections revealing different corrugation patterns; right, top: pleated airfoil with 5º angle of attack and Re = 10,000, 5,000, 1,000 and 500 (respectively from top to bottom), where the flow looks as if it pertains to the airfoils; right, bottom: detail of a recirculation zone in a valley of the wing [56].

additional merit in its compatibility with propellers or high lift devices. *Megaloprepus coerulatus* can glide without any impulse from the wings for more than 20 m at an angle of attack of 10º and with velocities up to 74 cm^{-1}, corresponding to a gliding ratio of 1:6, similar to that of some birds [57].

Drosophila melanogaster (fruit fly) features the ability to generate sideways forces during some manoeuvres on which they apply strong lateral acceleration associated with differences between the left and right wing angles of attack. Such asymmetry can be induced by altering the relative timing of flips between the right and left wings - fruit flies can employ timing differences as high as 10% of a wing beat period while accelerating sideways at 40% of gravitational acceleration. The sideway force is obtained by asymmetric rotation (flip) of both wings at the same time (see Figure 9). During sideway flight, each snapshot reveal the areas of the right and left wings: small wing area means the wing meets the air at a high angle of attack and thus generates large drag forces; large area means the wing is cutting through the air at low angle attack and thus feels small drag. This difference in the angle of attack between wings generate asymmetric drag forces that causes sideway flight; the unbalanced drag points to the left because the wings flap in large-amplitude arcs [57]. Observations on the hoverfly *Syritta pipiens* [58] indicate the ability to perform sideways without changing its heading. Such manoeuvre suggests that those animals possess independent control of roll and yaw, verified on research on the blowfly *Calliphora erythrocephala* flight, where roll and yaw often followed different time courses. Dragonflies and Damselflies are capable of fast flights and

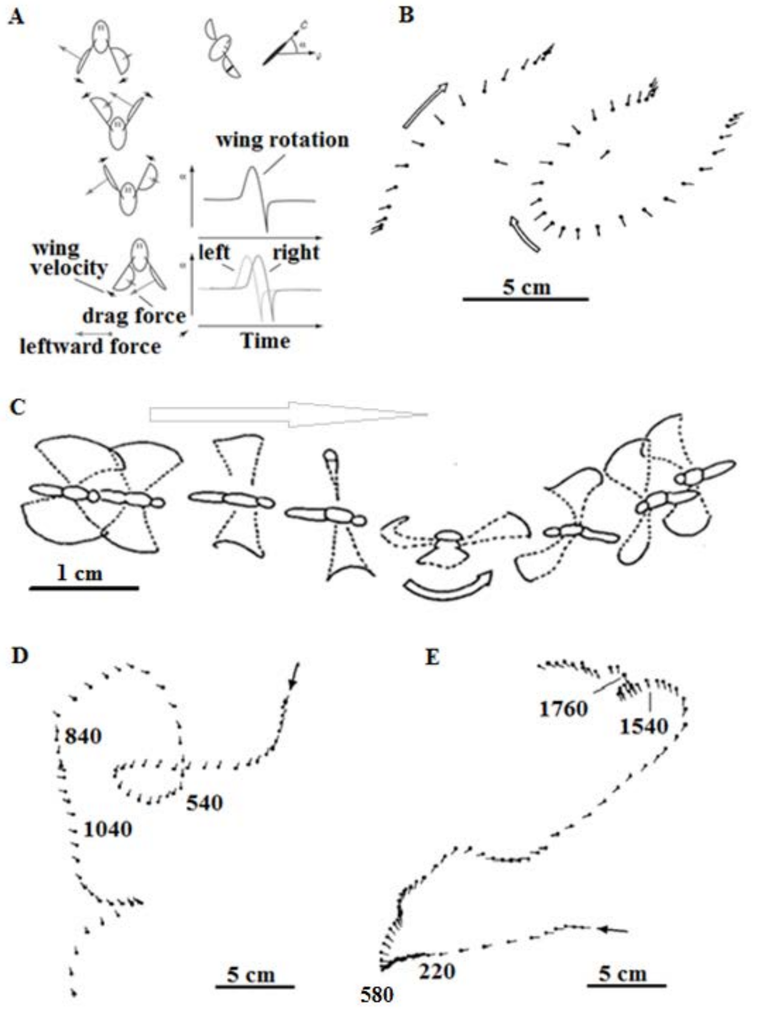

Figure 9: A) Schematic wing motion generating leftward force actuated by having the left wing rotate prior to the right [57]; B) *Hercostomus celer* sideway and circling flight pattern; C) *Poecilobothrus nobilitatus* detail of the display flight, using left wing as an air-brake to rotate its body anti-clockwise [60]; D and E) Examples of horizontal plane projections of flight tracking on hoverflies (1,400 ms) and honeybees (2,000 ms) respectively [50]. On B, D and E, the lines indicate body orientation (yaw) and the filled circles indicate the head position on every 20 ms of time interval.

great acceleration and desacceleration and can execute extremely rapid manoeuvres in a very limited space. Experiments of [59] on more than 20 species with different sizes the take-off acceleration (from 0 to 0,1 s) revealed the highest value of 25 ms^{-2} (*Sympetrum danae*); the highest acceleration from 01 to 0.2 s of flight revealed a value of 10 ms^{-2} (*Aeshna cyanea*); and the highest speed recorded in flight is 1,000 cm^{s-1} (*Aeshna cyanea*). The highest flight distance / wingbeat are 25 cm (*Aeshna cyanea*). The maximal acceleration obtained in all flights is 36.5 ms^{-2} (*Orthetrum cancellatum*). Some can fly at speeds up to 54 km/h [30]. The body shape of dragonflies probably reflects a selection by requirements of rapid flight: four-wings with large areas when compared to the body; large rounded eyes for a 360º visual acuity and an elongated abdomen for passive flight stability. During flight manoeuvres involved marking acceleration, *Orthetrum cancellarum* increase the stroke amplitude from ~80-90º while hovering, to a 130º during vertical take-off from the water. *Leucorrhina rubicunda* indicate a 90º stroke amplitude while hovering, to a 150º during vertical take-off with a female in mating position. *Calopteryx splendens* and *Calopteryx virgo* can fold their wings together over the abdomen after every or several wingbeats and hold them still, gliding like songbirds in ballistic flight, travelling relatively large distances per wingbeat. *Lestes viridis* during a simultaneous fore- and hindwings downstroke increased the flight velocity by as much as 40%. This acceleration could be also managed by employing large angles of attack during the upstroke. Large angles of attack were observed (57-75º) during a stroke away from the flight direction, and small (10-35º) during a stroke in the flight direction. In slow forward flight, the upstroke/downstroke ratio indicates 1/1.2 and in fast forward flight, the ratio indicates 1/1.9, with shorter upstroke. *Megaloprepus coerulatus* on a descended forward flight carrying a female on mating position reached an extremely short upstroke course time (upstroke/downstroke ratio 1/3). The upstroke/downstroke ratio of fore- and hindwings may also vary: in hovering and slow forward flight, the upstroke in hindwings indicate ~10% shorter than that of forewings (*Aeshna cyanea*, *Anax imperator* and *Calopteryx splendens*); ~35% shorter in *Lestes viridis*. The *Poecilobothrus nobilitatus* male fly, during his courtship behaviour perform a complex and notorious aerial performance: a D-shaped flight [60]: two arcs and one straight flight. The display flight is initiated with a pair of rather flattened 180º arcs around the female (the male finish this pattern of flight where he began). Then the fly perform a directly flight over the female, with an extremely fast (40ms) spin halfway (180º) which leaves the male flying backwards (completing the manoeuvre by decelerating backwards to a hovering stop. During these flights, the forward velocity reaches 0.6 ms^{-1}, the acceleration 12 ms^{-2} (1.2 g), the angular velocity 4,500 ms^{-1} and the corresponding angular acceleration is at least 225,000 ms^{-2}, while the inner wing is held out literally as an air-brake and the fly pivots around like a rower round as an oar. Previous results have shown that fruit flies mainly control force and moments by changing stroke amplitude of the two wings [61]. The hoverfly *Syritta pipiens L.*, revealed 4 different sideway flights excerpts: angular orientation saccadic change without a change on the course direction; change of course direction resulting exclusively from an angular orientation change; change of course orientation resulting from sideway velocity increase and forward velocity decrease; and also a mixture of the two last flight excerpts. The fastest tracking flights made by hoverflies - rapes -culminate in a rapid dart towards another hoverfly: in a rape, the male very frequently display a continuously acceleration (~500 cms^{-2}) and turning sideways (normally ~90º) before it lands; during the same rape, the forward acceleration is practically uniform and the sideways movements present much more variations.

Changes in the angle of attack have been observed to initiate low speed forward or backward flight acceleration [62]. Insects increase the angle of attack to a large upstroke or downstroke values and use the increased drag to initiate acceleration. The angles of attack on the drag-producing half-stroke often approach 90º and provide large horizontal acceleration. This “paddling / rowing” motion also rotates the body (and the stroke plane) in the correct direction because the drag force is applied above the centre of mass. As the stroke plane tilts, the increased drag would detract from weight support, and the insects revert to more normal angles of attack after only one or two wingbeats. The capacity of an insect to perform backwards flight it may be not displayed frequently, or if it is, it may very rapidly, lasting for several milliseconds, such as happens in the case of the Hoverfly *Syritta pipiens*; the hoverfly displayed a cruising flight (3s of flight with observed position every 20 ms) in which changed the angular position in a *saccade* performance, during which can fly forward, sideways and backward [58]. A 180º horizontal backward flight is reported to *Calopteryx splendens* (Zygoptera); the measured velocities of the wingtips in forward and backward flight on this insect were 180-310 cms^{-1}. A point halfway along the wing will move over half the distance and hence will have half that velocity, *i.e.*, 90-155 cms^{-1}. *Mercitogaster ornata* (Zygoptera) can change its wingbeat frequency from 15 Hz immediately after take-off to 20 Hz during rapid backward flight, and then to 15 and 13-5 Hz while hovering. *Lestes viridis* (Zygoptera), in tandem position beat its wings at 28,7 Hz during downward flight, compared with up to 35 Hz during straight forward flight and up to 37,5 Hz when flying steeply upwards and backwards. By employing a flight with parallel stroking (phase shifted by no more than 30º), *Mercitogaster ornata* is able to perform rapid backward flight and *Anisoptera* presented flight abilities requiring great force (rapid acceleration - backward upwards flight or carrying a female) in the range from straight up to horizontally backward flight, such flights in velocity conditions within 40 to 120 cms^{-1} and presenting mean and maximal acceleration values of 7 and 33.7 ms^{-1}, respectively. *Orthetrum cancellatum* displays a vertical backward take-off (flight direction approx. 100º) in parallel-stroking mode. A male *Calopteryx splendens* that had been slowly approaching a female in a counterstrokeing courting flight, advancing at a rate of 12,4 mm per wingbeat, can propel himself 46,5 mm backwards by only one parallel wingbeat. During take-off backward, *Megaloprepus coerulatus* (Zygoptera) the first forward stroke was executed with the wings at a steep angle (measured in the midregion of the downstroke), whereas in the first backward stroke the angle of attack was small; during the subsequent transition to straight forward flight, the wings were inclined at small angles in the middle of the forward stroke and at large angles during the backward stroke [59].

Free-flying mosquitoes not only can survive the high-impact of falling raindrops [63], as regardless of impact type (glancing – rotate the insect; direct – impact on insect body, pushing the animal for a considerable distance), they can recover quickly and resume flight. A raindrop could have a mass of 50 mosquitoes and a diameter <8mm, presenting falling velocities of ~5-9 ms^{-1}; a generic mosquito has a mass of ~0.002g and their velocity could be up to ~1 ms^{-1}. Mosquitoes possess hairy wings; such hair, increase the wing surface area and so its energetic cost of wetting – the hair contributes a hydrophobic wings; low simply drops simply bounce off the insect. The mass of the insect determines the acceleration and speed after the impact; firstly mosquitoes survive by using their low mass relative to raindrops; due to differences of mosquito/drop mass, the mosquitoes slow raindrops by only ~1-17%; because of the impact, mosquitoes are accelerated by 30-300 G for 1 ms. The impact of 9 ms^{-1} accelerates the mosquito to a velocity of 2.1 ms^{-1} within duration of 1.5 ms; after tumbling a distance pf 39 mm (13 body lengths) the mosquito separates laterally from the drop and land safely. The glancing impacts cause a pitch, yaw, or roll to insect depending on the impact point; the insect tends to recover its original position in 0.01 s. Such understanding of insects flight in the natural world, exploit new adaptations via biological inspirations for the design of robust MAVs or NAVs.

In addition to varying the wing kinematics, several insects could manage their longitudinal and lateral flight control by deflecting their own body while in-flight. *Drosophila melanogaster* could elevate their abdomen in response to nose-down disturbances, thus displacing the centre of gravity dorsal to the line of thrust, which therefore generates a restoring nose-up moment with the inertia of the fly´s body. Other similar postural changes have been observed in *Calliphora erythrocephala*. *Drosophila virilis* have also been observed to elevate their hindlegs following a nose-down disturbance, which should increase drag dorsally and generate a nose-up pitching moment; such hindlegs movement could have interference from the wake of the wings, and so enhance the fly´s turning effect. Locusts appear to regulate lift independent of thrust and have also been claimed to exhibit a “constant-lift reaction” in which the vertical component of the force is kept more or less constant following by imposed changes of body angle of up 20º. Related to lateral control using postural changes, such *Calliphora erythrocephala* and *Drosophila melanogaster* could manage a delayed supination on the inside wing and advanced supination on the outside wing have been observed during fictive turns. Lateral movements of hindlegs and abdomen have also been observed in response to visual roll stimuli in locusts (*Orthoptera*). Similar postural adjustments appear to be ubiquitous steering responses in insects and have been reported in mantids, heteropteran bugs, strepsipterans, and moths [63].

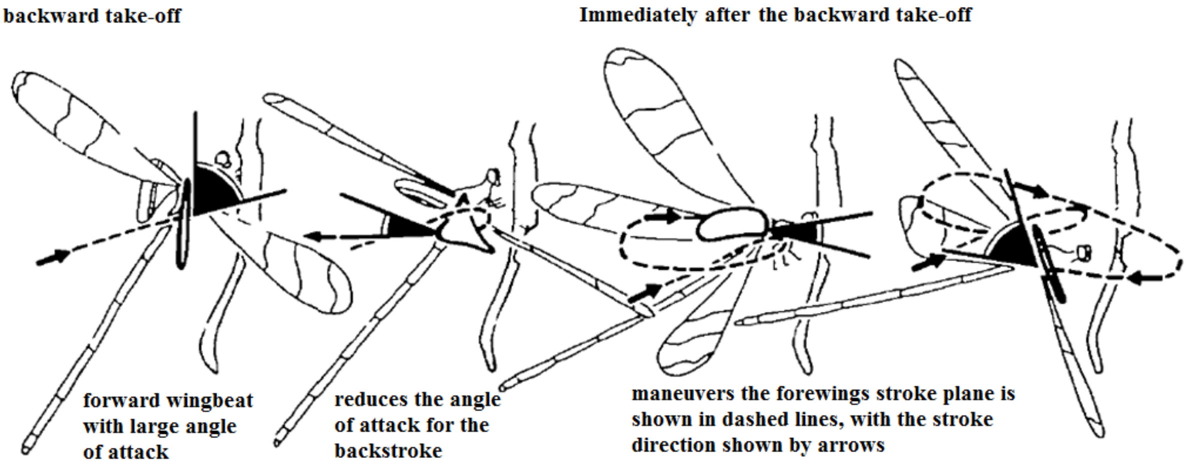

Figure 10: Elusive sketch of a *Megaloprepus coerulatus* backward take-off immediately followed by forward flight [59].

3 CONCLUSIONS

The natural flight ability of animals has been an active research in recent years that provided inspiration on their manoeuvrability and agile flight, for the design and control of MAVs and NAVs. Nevertheless, biomimetic engineered devices are still far from the living organisms and more research is needed. There is a general agreement that an unsteady dynamics approach is required to capture the physical phenomena at this scale. Additionally, propulsion and lift should not be considered independently. Flapping wing systems appeared in animals such as insects, birds, and fishes, which are known to exhibit remarkable aerodynamic and propulsive efficiencies. Flapping wings induce angular, centripetal and Coriolis accelerations in the air near to the wing's surface, which diffuse into the boundary layer of the wing. Some results suggest that swimming and flying animals could control de predictability of vortex-wake interactions, and the corresponding propulsive forces with their fins and wings.

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