ABSTRACT

BUNGET, GHEORGHE. BATMAV: A Biologically-Inspired Micro-Air Vehicle for Flapping Flight – Kinematic Modeling. (Under the direction of Stefan Seelecke.)

The main objective of the BATMAV project is the development of a biologically inspired bat-like Micro-Aerial Vehicle with flexible and foldable wings, capable of flapping flight. This phase of the project starts with an analysis of several small-scale natural flyers from an engineering point of view with the objective to identify the most suitable platform for such a vehicle. Bats are shown to be very agile and efficient flyers with mechanical parameters well-suited to be realized with currently available muscle wire actuators allowing for close bio-inspired actuation. The second part of this thesis focuses on the kinematical analysis of the wing motion with the intent to develop a smart material (shape memory alloy) driven actuator system mimicking the functionality of the bat's relevant muscle groups in the future.

In the past decade Micro-Aerial Vehicles (MAV's) have drawn a great interest to military operations, search and rescue, surveillance technologies and aerospace engineering in general. Traditionally these devices use fixed or rotary wings actuated with electric DC motor-transmission, with consequential weight and stability disadvantages. SMA wire actuated flexible wings for flapping flight are promising due to increased energy density while decreasing weight, increased maneuverability and obstacle avoidance, easier navigation in small spaces and better wind gust stability. While flapping flight in MAV has been previously studied and a number of models were realized using light nature-inspired rigid wings, this paper presents a platform that features bat-inspired wings with flexible joints and muscle-wire actuation to allow mimicking the kinematics of the real flyer.

The bat was chosen after an extensive analysis of the flight physics of birds, bats and large insects. Typical engineering parameters such as wing loading, wing beat frequency etc. were studied and it was concluded that bats are a suitable platform that can be actuated efficiently using micro-scale Flexinol muscle wires. Also, due to their wing camber variation, they can operate effectively at a large range of speeds and allow remarkably maneuverable flight, avoiding obstacles while flying in small spaces (i.e. search and rescue missions).

In order to understand how to implement SMA ‘mechanical muscles’ on a bat-like platform, the analysis was followed by a study of bat flight kinematics. Due to their complexity, from the engineering point of view, only a limited number of muscles were selected to actuate the flexible wing. A computer model of BATMAV platform incorporating SMA wires, wings and platform body, was created using SolidWorks software. The skeleton was subsequently fabricated using rapid prototyping technologies, and a novel joint technology was introduced which, replaces the complicated morphology of the natural flyers by a combination of superelastic SMA wires as flexible hinges. An extended analysis of flight styles in bats coordinated with image processing and inverse kinematics theory for robotic manipulators resulted in a collection of data for joint angles variation of the wing bone structure. These data implemented into the direct kinematics of the ‘robotic-like wing arm’ helped to mimic the wingbeat cycle of the natural flyer.

BATMAV: A Biologically-Inspired Micro-Air Vehicle
for Flapping Flight – Kinematic Modeling

by
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BIOGRAPHY

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CHAPTER 1

INTRODUCTION

Micro Aerial Vehicles (MAVs) are a group of Unmanned Aerial Vehicles (UAVs) that are significantly smaller in the overall dimensions and weight, with a size of approximately six inches. There has been much interest in MAVs especially for applications where maneuverability in confined spaces is necessary, i.e. internal inspection of pipes, exploration around rubble in collapsed buildings and surveillance of indoor environments. Other missions of interest for MAVs include detection, communications and placement of unattended sensors. Due to the availability of very small sensors, detection missions include the sensing of biological agents, chemical compounds and nuclear materials, i.e. radioactivity. Because these vehicles may fly at relatively low altitudes, i.e. less than 300 ft where buildings, trees, hills, etc. may be present, maneuverability is an important factor to avoid collision. Furthermore, since these vehicles have essentially small flying wings, there is a need to develop efficient low aspect-ratio wings which are not overly sensitive to wind shear, gusts, and roughness produced by precipitation.

In the mid 90's, the Defense Advanced Research Projects Agency (DARPA) started a research program that led to the development of the first serious generation of MAVs. These vehicles were airplane-like models with fixed wings, propeller driven and could carry a battery, cameras, R/C transmitters and micro servos for flight control, and could fly for about 20 minutes. They typically weighed around 50g, extended less than 6 inch in all dimensions and were almost exclusively characterized by a rigid wing design with discrete rudders and flaps actuated by micro servos via a rod or wire system. There are three general trends of MAV under investigation: (a) airplane-like models with fixed wings, (b) helicopter-like models with rotating wings, and (c) bird or insect-like models with flapping wings.

This research aims at implementing a model with flexible wings for flapping flight. SMA wires actuation is replacing the motor and transmission actuation of the traditionally designed MAV. The actuation with SMA wires is a step toward a higher level design for a flexible wing having articulated joints originating from very efficient designs of natural flyers.

In actuator technology, active or “smart” materials have opened new horizons in terms of actuation simplicity, compactness and miniaturization potential. The small size and high force capabilities of SMA wires are more likely to result in a simple actuation mechanism with no additional motion reduction or amplification hardware. These merits permit the realization of small or even miniature actuation systems in order to overcome the weight and space limitations for a MAV design. A salient quality of these wires is that they operate like a mechanical “muscle” when they are excited by an electric impulse. After a SMA wire had been deformed, the shape memory effect of SMA wires enables them to contract and regain their original length during heating.

Another spectacular feature of SMA wires is that they have a very high elasticity to develop a flexible wing. Due to their super-elasticity and shape memory effect, SMAs can produce large recoverable deformations and generate large actuation forces. Due to their high elastic strains, the SMA wires can be reversibly bent providing up to 180° angle deformation (compared to ~5° for conventional spring steel), which makes them suitable to model the wing joints.

CHAPTER 2

REVIEW ON THE MAV AND ON THE FLIGHT OF SMALL NATURAL FLYERS

2.1. Review on the MAV

In the past decade Micro Aerial Vehicles (MAVs) have drawn a great interest to military operations, search and rescue, surveillance technologies and aerospace engineering in general. Traditionally, these devices use fixed or rotary wings actuated with electric DC motor-transmission, with consequential weight and living a little interior room in the device for control systems and payload. There are three general trends under investigation:

a) *Airplane-like models with fixed wings* – During the last decades many prototypes of airplane-like designs of small size for forward flight were built with a wingspan close to 30 cm. Yet the decrease in dimensions brought with the disadvantage of a loss in efficiency. Figure 2.1 presents the model studied at the University of Florida (Abdulrahim et al., 2005).

Figure 2.1: Airplane-like model of MAV (Abdulrahim et al., 2005).

b) *Helicopter-like models with rotating wings* – A helicopter-like MAV called mesicopter, weighing 15g was developed at Stanford University that uses miniature rotorcraft technology (Figure 2.2).

Figure 2.2: Mesicopter prototypes, a helicopter-like MAV (Kroo and Prinz, 2000).

c) *Bird or insect-like models with flapping wings* – Once the construction of small air vehicles became possible using miniaturized electronics and avionics devices, the interest in flapping flight emerged again from the eras of Leonardo Da Vinci and Lilienthal. In the last five years, advances have been made towards a more flexible wing design using composite materials in order to decrease the gust sensitivity and to increase the control (Figure 2.3). Pornsin et al., 2000, developed a remarkable technology to create bat-like wings and other insect wings, using titanium-alloy metal as wingframe and parylene C as wing membrane (Figure 2.4). A transmission mechanism was used to convert the rotary motion of the driving DC motor into the flapping motion of the wings. The bat wings weighted 170 mg, and they could withstand more than 30 Hz of flapping without breaking. Flight duration of 5 to 18 seconds was achieved.

Figure 2.3: A biologically inspired approach to improve the efficiency of airplane-like models (Abdulrahim and Lind, 2004).

Figure 2.4: MEMS fabricated silicon wings (Pornsin et al., 2000)

Altogether, it can be said that the current systems have reached a certain level of maturity at this scale, but their potential for further development appears rather limited. The traditional designs with fixed or rotary wings actuated with electric DC motor-transmission have the consequential disadvantage of heavy platform and less stability. In order to benefit from the continuous miniaturization process in electric components, and to enable new applications like Mars research surveillance missions, a drastic improvement in the structural design is needed.

Several groups have worked on MAVs with fixed and rotary wings and only few groups have studied flapping-flight MAVs, which can provide superior maneuverability beneficial in obstacle avoidance and navigation in small spaces. Even though the MAVs developments are impressive, the field of flapping wing MAVs is still in its infancy and its present technology has not yet reached the level of optimization achieved by natural flyers and therefore, this work can be seen as a step towards the accomplishment of such a level.

2.2. Analysis of Morphological and Flight Parameters of Small Fliers

In order to choose an optimal type of natural flier wing as a model for the MAV design, a number of small natural fliers were thoroughly analyzed. The morphological and flight parameters are compared in order to choose an optimal wing structure that will comply with the SMA parameters, particularly wingbeat frequency, wingbeat stroke and body mass. One first constraint for a MAV design is that, by definition a MAV must have a total wingspan less than 6 inch, which makes the analysis of natural flyers to be within the range of small birds, like hummingbird, small bats and large insects. A large interest in study the flight of insects, bats and birds was manifested in the circle of biologists and a synthesis of their conclusions follows in next sections.

2.2.1. Comparison of Morphological Parameters

Mechanical calculations depend on measuring the physical parameters of a flyer, and on their combination. Relevant aspects of morphological data and airframe measurements were collected from existing literature and the small species with a body mass smaller than 10g

were analyzed. The most encountered morphological parameters in the studies on biological flight, as well as their influence on the mechanical and flight parameters are described as it follows.

Since dimensions of the analyzed flyers are varying drastically from small bats to large insects, in order to have a clear understanding of the wing capabilities it is useful to consider the ratio of these parameters to the flyers body mass. In this way the performance of a small wing, i.e. insect wing, can be more appropriately compared with a large wing of 6 inch span of a bat.

Wingspan, b , is the most important morphological measurement required on a flyer, after body mass. It is the distance between the two wing tips when the wing is fully extended as during the downstroke:

$$b = 2R + w, \quad (2.1)$$

where R is the wing length, and w is the body width. A longer wingspan is generally more efficient because the flyer suffers less induced drag and its wingtip vortices do not affect the wing as much. However, the long wings mean that the flyer has a greater moment of inertia about its longitudinal axis and therefore cannot roll as quickly and is less maneuverable.

Figure 2.5 shows that the dragonflies have a longer wingspan per each gram of body mass. Yet, adopting a dragonfly-like wing for a 10 gram MAV would increase the needed wingspan much beyond the limit of 6 inch expected. The specific values of wingspan for bat, hummingbird and hawkmoth are quite similar. The relative low specific wingspans in bats allow them to have a maneuverable flight even though this makes a larger drag for high velocity flight.

Table 2.1 shows that the high wing loading and low aspect ratios of bats also allows them to carry weights, such as their youngsters, without too much trouble. Since the wing loading is a function of mass, this, obviously temporarily, increases its wing loading also and it was observed that their wing design allows them to almost double their wing loading. Also, the wing design of insectivore bats operates as a fairly maneuverable flight platform allowing them to hunt between vegetation and to be heavy transporters when fully loaded.

Figure 2.5: Wingspan comparison: a) Absolute value; b) Specific value – wingspan reported to body mass.

Table 2.1: Mean morphological data and flight parameters for different species of bats.

Bat Name	Body mass m [g]	Wing span R [cm]	Wing span area S [cm ²]	Aspect ratio AR	Wing loading fw [N/m ²]	Flight speed range v [m/s]	Wingbeat frequency f [Hz]	Wingbeat amplitude θ_w [°]
<i>Hipposiderus Ater</i> ¹	4.4	24.9	106.1	5.8	4.07	2-4.7	10.9	57±9
<i>Vespadelus regulus</i> ¹	4.7	23.35	89.1	6.12	5.17	5	10.7	41±7
<i>Vespadelus Finlaysoni</i> ¹	5.6	25.5	104.2	6.24	5.3	4-8	10.7	58±10
<i>Scotorepens Greyi</i> ¹	7	25	101	6.2	6.8	6.7-8	11.6	60±18
<i>Scotorepens Balstoni</i> ¹	8	26.6	113	6.27	6.95	3.3-5	11.3	35±8
<i>Mormopterus planiceps</i> ¹	8.6	26.35	95.9	7.25	8.69	8.1	9.3	40.7±10
<i>Nictophilus Gouldi</i> ¹	10	30.5	159.7	5.82	6.14	1.7-5.8	10.4	59±11
<i>Miniopterus schreibersii</i> ¹	10.1	34.09	167.4	6.94	5.91	5.8	9.1	92.5±18
<i>Plecotus auritus</i> ²	9	27	123	5.9	7.18	2.35	11.9	90.7

1- Data from (Bullen and McKenzie, 2002)

2- Data from (Betz, 1958)

Wing loading, p_w , is the ratio of body weight, mg , born by a wing to its surface area, S :

$$p_w = \frac{mg}{S}, \quad (2.2)$$

Wing loading is the weight per unit wing area, in other words the mean pressure difference between the lower and upper surface of the wing when the bird is in a steady glide. Lower wing loading permits slower flight without stalling. Wing loading is broadly reflective of the aircraft's lift-to-mass ratio, which affects its rate of climb, load-carrying ability, and turn performance. Airplanes with lower numbers for wing loading do not need as much air flowing around the wing to keep it flying.

Wing area tends to increase with the square of linear body dimensions, while body mass is a function of volume and increases with the cube of linear dimensions. So, the ratio of body weight to wing area tends to increase linearly with body dimensions, thus it is larger in larger animals and aircraft. Wing area is related to the mean pressure force over the wings and therefore proportional to the square root of the flight speed. Animals and aircraft with low wing loadings can therefore fly slowly and still produce necessary lift, whereas larger flying animals and aircraft have to fly faster.

Maneuverability is also dependent on wing loading; the minimum radius of turn is proportional to body mass. Small bats and birds with low wing loadings are therefore more maneuverable than larger animals with higher loadings. Therefore airplanes used in aerobatics need to be small with wide wings to have a low wing loading. For birds, wing loading ranges from 18 N/m^2 for a small hummingbird to 230 N/m^2 for the whooper swan.

Comparing the wing loading, Figure 2.6 shows that hummingbirds have a higher absolute value of wing loading and that small bats are classified on the second place. This comparison shows also that butterflies have the least wing loading, which makes them to be very maneuverable and also to need a lower wingbeat frequency to maintain the flight. Lower wing loading permits a slower flight without stalling, helping in turn performance and in flying in confined spaces.

Figure 2.6: Comparison of wing loading.

Aspect ratio, AR , describes the shape of the wings and is defined as the ratio of the wingspan and its mean chord. It is calculated as wingspan squared divided by wing area:

$$AR = \frac{b^2}{S}, \quad (2.3)$$

where b is the wingspan and S is the wing area.

Aspect ratio is a powerful indicator of the general performance of a wing. Wingtip vortices greatly deteriorate the performance of a wing, and by reducing the amount of wing tip area, making it skinny or pointed for instance, the amount of energy lost through induced drag, can be reduced.

Wing loading and aspect ratio quantify the size and shape of the wings, and they measure the aerodynamic efficiency. A higher aspect ratio indicates a relatively narrower wing. At a constant angle of attack, a reduction in the aspect ratio will result in a reduction in the lift coefficient, C_L . The aerodynamic performance can be improved by increasing the aspect ratio, making the wings longer and thinner, as it is done in modern sailplanes. The longer the

wings are, the smaller the wingtip vortices become and the induced drag, thus the mechanical energy costs of flight will be lower. This aspect is important for slow-flying species where induced drag is a dominant component of the total drag. Shallower glide angles are also permitted with a high aspect ratio. High aspect ratio wings are associated with a reduced power cost to create comparable lift.

But long wings are not always advantageous. Very long wings are more vulnerable to breakage and in animals they can be of hindrance in a cluttered environment and limit take-offs from the ground. Aspect ratio ranges from around 4.5 in some galliforms up to 15–20 in albatrosses. It is around 20 in high-performance gliders, whereas airplanes used in aerobatics have short, broad wings for high maneuverability. Jumbo jets have aspect ratios around 7 and Concorde as low as 1.8.

Figure 2.7 compares the aspect ratio, and it can be observed that the damselfly wing has the highest aspect ratio between the studied flyers, making them suitable for gliding flight with a reduced amount of energy lost through wingtip vortices.

Figure 2.7: Aspect ratio comparison.

2.2.2. Comparison of flight parameters

a) **Wingbeat frequency** – This is one of the most interest flight parameter for this research is the. The main morphological parameters that affect the wingbeat frequency are body mass, wing span, wing area and the moment of inertia of the wing. Using a combination of multiple regressions and a dimensional analysis, Pennycuick, 1990, estimates the wingbeat frequency for birds with the following formula:

$$f = \frac{1.08}{b} \sqrt[3]{\frac{m}{\rho}} \sqrt{\frac{g}{S}}, \quad (2.4)$$

where m is the body mass, g the acceleration due to gravity, b the wing span, S the wing area, and ρ the air density. This estimate shows that the larger the wingspan the smaller is the wingbeat frequency to keep aloft the flyer, and that the body mass should be balanced by an increase in wingspan and in wing area in order to reduce the wing frequency. Therefore, adopting a wing type of an insect in order to use for a MAV of 10g of body mass should be followed by a correspondent increase of wingspan and wing area. Table 2.2 presents a list of parameters for hummingbirds.

Table 2.2: Mean morphological data and flight parameters for two species of hummingbirds.

Variable	<i>Selasphorus rufus</i>		<i>Archilochus colubris</i>	
	Hovering	Forward	Hovering	Forward
Body mass, m [g]	3.2		4.2	
Single wing length [cm]	4.6		4.4-5	
Wing span, R [cm]	10.5			
Average chord [cm]	1.3			
Aspect ratio, AR	7.1		7.5	
Single wing area [cm ²]	5.9			
Wing loading [N/m ²]	36.7±3		38±5.9	
Disc loading [N/m ²]	3.7		4.1	
Wingbeat frequency [Hz]		44-56	49±4	
Stroke amplitude [°]		145-166	156±15	

Data from [TobalskeEtal04]

The data from Table 2.1 and 2.2 regarding to wingbeat frequency plotted in Figure 2.8 shows that butterflies and bats have the lowest wingbeat frequency which makes their wings

feasible to be actuated by Shape Memory Alloy (SMA) wires, the latest having an upper limit for frequency of 13Hz. It can be seen that the wingbeat frequency for bats is around 10 Hz. The long-eared bat, *Plecotus auritus*, is a low-speed flier, but is very good in maneuvering, and hovers easily.

Figure 2.8: The wingbeat comparison.

For the wing of the other flyers, in order to reduce the frequency as long as their body mass is increased up to 10 g, their product wingspan-wing area, $b \times S$ should be increased significantly. Figure 2.9 shows crude estimates of the increased wingbeat frequency per each gram of body mass. It can be seen that for butterfly wing, the wingbeat would increase significantly, especially for light species. This crude estimates of exerted wingbeat frequency per gram of weight shows that the bat wing has a higher efficiency requiring a low frequency to sustain the animal weight during flight.

In flight, the wings produce lift, and the vertical component of lift is the upward force that counteracts the flyer's weight. The direction of the lift is always normal to the wing, and when the wing is in a horizontal position the lift will be vertical and the upward force is the same as the lift (Figure 2.10). If the upward force is greater than the weight, the flyer will rise.

The lift and thrust forces produced by a flapping wing are increased with the size of the airfoil.

Figure 2.9: Comparison of the specific wingbeat frequency.

Figure 2.10: Forces associated with flight.

b) **Drag Forces** – These are the forces acting on every object moving within a fluid. The component of force parallel to flow is called drag and is the combined effect of *pressure drag* and *viscous drag* (also called *frictional drag*). *Pressure drag*, also known as *inertial drag*, is highest at the most anterior point of contact between the moving object and fluid. Both pressure and viscous drag depend of the relative fluid velocity V and of object dimensions. At low velocities of flight, drag is caused largely by viscosity of the air. The wings experience a third type of drag, the *induced drag*, which comes from the same process that generates lift.

The ratio of inertial to viscous forces varies with the ratio of the fluid density and the fluid viscosity (Dudley, 2000). The formulation of these parameters is the *Reynolds number*, Re , which is given by:

$$Re = \frac{\text{Inertial Drag}}{\text{Viscous Drag}} = \frac{\frac{\rho V^2}{l}}{\frac{\mu V}{l^2}} = \frac{\rho l V}{\mu} = \frac{l V}{\nu}, \quad (2.5)$$

where l is a characteristic dimension of the flyer, ρ the air density, μ the dynamic viscosity, and ν the kinematic viscosity. The Reynolds number expresses a quantitative description of variable flow regimes. The air flow is usually laminar below Re of 1000 – 10000, while turbulence is larger at higher Re . The flight of small birds and insects can be characterized by two estimates of Re , one for wings and the other for body. Body length is the characteristic dimension for the Re of body in forward flight, and the mean wing chord, c , is the relevant quantity for Re of wings. The mean wing chord, c , is the mean distance between the leading and the trailing edge of the wing, and it is calculated by:

$$c = \frac{S}{R}, \quad (2.6)$$

where S is the wing area and R is the wing length.

The Reynolds number determines whether viscous drag or pressure drag should be dominant. At Reynolds numbers between 0 and 1, viscous drag is more important, and for $Re > 1$, pressure drag is more important. For most flying animals, pressure drag is of much more importance than viscous drag, although for insects the viscous drag becomes significant.

The total air drag D acting on a flier is the sum of the effects of pressure and viscous drag. The comparison of drag of different fliers is facilitated through the definition of a non-dimensional drag coefficient C_D , which is calculated by:

$$C_D = \frac{2D}{\rho S V^2}, \quad (2.7)$$

Drag coefficients of both flier wings and bodies tend to decrease at higher Re . Equation (2.7) refers only to motion at constant velocity. For accelerating flight regimes an additional force is required to body drag to accelerate the added mass of surrounding air entrained by the flier's motion. Because we analyze the flight of small fliers (small size), and since the air density is low, these additional forces are insignificant in comparison with viscous and pressure drag.

c) **Lift Forces** – Just as drag is the force parallel to flow, lift is defined as the component of force orthogonal to flow and so perpendicular to drag. The lift and drag forces of the wing are defined relative to the direction of the airflow over the wing, not relative to the directions in which the animal flies or gravity acts (Figure 2.11). As a rule, lift is perpendicular and drag is parallel to the direction of the airflow. Lift and drag have a resultant force, R , which is tilted forward during the downstroke and because of this it has a vertical component, the upward force U , and a horizontal component that is tilted forward, and so it is providing the thrust T . The wing moves down and forward during the downstroke, so do the lift, L , and the resultant force, R , which the sum of lift and drag, D , are tilted forward and so it has a forward component, the thrust – T , and the weight supporting upward component – U ; α is the angle of attack.

For most fliers, the lift forces are small in comparison with drag. As with drag, the total lift L can be expressed through definition of a lift coefficient C_L :

$$C_L = \frac{2L}{\rho S V^2}, \quad (2.8)$$

We can use this relation to compare the lift production of a wing at different Reynolds numbers or the lift produced by different wings at the same Reynolds number. From relation

(2.8) it could be concluded that a small increase in speed yields a large increase in the lift force. Also, the area of the wing, S , has an effect on the lift production: the more area of wing, the more area to generate lift.

Figure 2.11: Forces on a flapping wing during the downstroke.

An important characteristic of a given airfoil is the lift to drag ratio, L/D (Figure 2.12). The flyer's weight sets the lift requirement, since the wing must produce enough upward force to balance the weight of the flyer. And, since drag is balanced by thrust, the higher the lift to drag ratio of the airfoil, the less thrust is needed to produce that required lift.

Figure 2.12: Comparison of the lift to drag ratio.

The aspect ratio, AR, is another feature that has an important influence on lift production because of its effect on tip vortices. A *vortex* is a flow pattern where the fluid follows a circular path, as in a whirlpool or a tornado (Alexander, 2002). As the wing starts moving, it produces a starting vortex, which rolls off the trailing edge (Figure 2.13, a), and turns in the opposite direction to the bound vortex. As the wing moves away from the starting vortex, the bound vortex stays attached to it by a trailing or tip vortex off the end of each wing tip (Figure 2.13, b).

Figure 2.13: (a) Bound and starting vortices, (b) Computer simulation of a vortex ring wake for magpie (Rayner, 1998).

The vortices form a system like a distorted smoke ring, and as the tip vortices stream off each end of the wing and trail along behind the wing as long as the wing produces lift. As air spills upward around the end of the wing, the produced turbulence, known as the wing tip vortex, increases drag and loses some lift produced near the wing tip. A short and broad wing with low aspect ratio has effectively more tip for its area than a long and slender wing with a higher aspect ratio, and so it has a stronger tip vortex. Therefore, the low aspect ratio wing has more induced drag than the high aspect ratio wing. Thus, long and narrow wings have a lower induced drag and a higher lift-to-drag ratio, L/D , than short and broad wings, as it could be seen in the Table 2.3. Lift-to-drag ratio is the amount of lift generated by a wing, compared to the drag it creates by moving through the air. A "better" L/D ratio is one of the major goals in wing design, since a particular aircraft's needed lift doesn't change, delivering that lift with lower drag leads directly to better fuel economy, climb performance and glide ratio. Therefore, lift-to-drag ratio has the tendency to increase with the size of the flyer. At small sizes, the Reynolds numbers are low, which makes that viscous drag to be more

important. The viscous drag inhibits the formation of the bound vortex and reduces its strength. The result is a low lift production. So, at low Reynolds numbers, lift-to-drag ratios are small. Thus, for small flyers like insects, with lift to drag ratios less than 2, gliding is a little better than falling, becoming very impractical.

Table 2.3: Aspect ratios and lift-to-drag ratios for different flyers (Alexander, 2002).

Flyer	Aspect ratio	Lift-to-drag ratio
Fruit fly	5.5	1.8
Bumblebee	6.7	2.5
Crane fly	6.9	3.7
Sparrow	5.3	4
Swift	11	10
Falcon	8.5	10
Red-tailed hawk	7.1	10
Turkey vulture	7	15.5
Stork	7.8	10
Wandering albatross	15	19

In horizontal flight, the lift increases when the angle of attack of an airfoil (the cross-sectional shape of the wing) increases, as seen in the Figure 2.14. This is an advantage that can be used to get more lift, but it must be used for angles smaller than the critical value to avoid the stall of the wing. The critical angle depends on the airfoil shape and on the Reynolds number. For a large bird, the critical angle is approximately 20° , for a grasshopper is about 30° , and for a fruit fly is about 50° (Alexander, 2002).

Figure 2.14: The influence of the angle of attack to the lift production: (a) Moderate lift for no angle of attack; (b) As the angle of attack, α , increases, lift also increases (Alexander, 2002).

d) **Thrust** - The wings produce lift as long as the flyer moves forward, like in gliding, but flapping allows the wings to generate a forward force while producing an upward force passively. A flyer overcomes the drag forces by producing thrust. So, flying animals flap their wings only to produce thrust, not to produce lift. To generate more thrust, the flyers flap their wings in a path tilted downward and forward from the vertical (approx. 30° from the vertical) during the downstroke, and in a path tilted upward and backward during the upstroke. The wing tips of some flyers have a relatively simple path, such as an oval tip path for albatross or a figure of eight for pigeon. In general, there is the following rule: the larger the flyer and the faster the flight, the closer the tip path approaches simple harmonic motion (Figure 2.13, b), like a symmetrical sine wave, and as the flyers get smaller and their flight speeds get lower, the tip paths become more and more distorted and asymmetrical.

Usually the downstroke lasts longer than the upstroke, and this asymmetry is largest in slow flight and smaller in fast flight (Table 2.4). In this table a ratio of 1.0 means that the downstroke lasts exactly as long as the upstroke, while a ratio of 2.1, as for slow gait of bats, means that the downstroke lasts 110% longer than the upstroke.

Table 2.4: The ratio between the downstroke and the upstroke for different flyers (Alexander, 2002).

Flyer	Downstroke to upstroke ratio
Albatross	1.06
Vulture	1.4
Bat (fast gait)	1.31
Bat (slow gait)	2.1
Dragonfly	1.37
Honeybee	1.3
June beetle	1.5
House fly	1.5
Locust	1.9
Fruit fly	1.7

The downstroke differs also from the upstroke through the angle of attack of the wing. A flapping animal holds its wings at a higher angle of attack during the downstroke and at a

lower or even negative angle during the upstroke. Additionally, birds and bats change the area of their wings on the upstroke and downstroke. All these differences between downstroke and upstroke are crucial for thrust generation, otherwise, if the downstroke and the upstroke would be symmetrical, the wings having the same angle of attack and the same duration, then their horizontal components would cancel and the wings would not produce any thrust.

e) **Mechanical Power Requirements** – In steady forward flight, there are four distinct components of mechanical power: parasite power P_{par} , induced power P_{ind} , profile power P_{pro} , and inertial power during the first half of half-stroke, P_{acc} .

Parasite power (P_{par}) is the rate of working needed to counteract form and friction drag of the body, it can be said that is the power needed to propel the flyer's body, excluding the wings, through the air. For steady horizontal flight, not accelerating in any direction, it can be represented by:

$$P_{par} = D_b V, \quad (2.9)$$

where D_b is the parasite body drag. The drag D on a plate of area A , which brings the wind completely to a stop, is $D = pA$, where p is the dynamic pressure (Pennycuick, 1989). The value of A , which results in the same amount of drag as that produced by the flyer body, is said to be its equivalent flat plate area. Yet the actual frontal area of the body, S_b , is greater than A , because the body is streamlined, and only slows the wind down a little, without bringing it to a stop. If the flyer body produced the same amount of drag as a flat plate with 20% the cross-sectional area, then the equivalent flat plate area would be $0.2S_b$, and we note $C_{Db} = 0.2$ as being the *drag coefficient* of the flyer's body. So, it can be written that

$$D_b = \frac{1}{2} \rho V^2 A = \frac{1}{2} \rho V^2 S_b C_{Db}, \quad (2.10)$$

Plugging in equation (2.9) will give

$$P_{par} = \frac{1}{2} \rho V^3 S_b C_{Db}, \quad (2.11)$$

It could be assumed that A can be estimated from the formula given by Pennycuick, 1972, which can be re-expressed as:

$$A = (2.85 \times 10^{-3}) m^{\frac{2}{3}}, \quad (2.12)$$

where the equivalent flat plate area, A , is in $[\text{m}^2]$, and the body mass, m , is in $[\text{kg}]$. It is difficult to make accurate drag coefficient measurements, but ‘best guess’ estimates are in the region of 0.25 for flyers like geese and swans, 0.40 for small birds, and intermediate for pigeon-sized flyers (Pennycuick, 1989).

Induced power, (P_{ind}) is the power required to support the weight of flyer in air, and thus, it is the rate of working required to generate a vortex wake whose reaction generates lift and thrust. The induced power is the principal power component in hovering and slow flight. (Norberg et al., 1993, compares a hovering animal to a helicopter whose rotors drive the air downwards through the disk formed by the sweeping rotor blades. Pennycuick, 1975, derived an expression for the induced power of a bird in horizontal flight. For this, the flyer is considered as being stationary and the air flowing past it at the flight speed V . In steady horizontal flight the flyer is supporting its weight through an upward reaction (the lift force, L) by pushing down the air during downstroke flapping (Figure 2.15). As a result, the air is accelerated downward, but part of this air is accelerated before reaching the wing disk.

Figure 2.15: The action of the flyer’s wings makes the air to accelerate downward.

The flyer flaps its wings, sweeping out a wing disk of area S_d . The action of the wings causes the air to accelerate downward. Part of this acceleration occurs before the air reaches the

disk, being caused by reduced pressure on the dorsal and forward sides of the disk. This action results in the air attaining a downward induced velocity V_i as it passes through the disk. The region of increased pressure behind and below the disk, which is a mirror image of the area of reduced pressure ahead and above, continues to accelerate the air downward until far behind the bird, where it reaches an eventual downward velocity $2V_i$. The rate at which downward momentum is imparted to the air is the product of the mass flow (mass per unit time) passing through the disk, of area S_d , times the eventual downward velocity $2V_i$, and this rate of change of momentum must equal the weight of the flyer, W :

$$W = VS_d\rho \cdot 2V_i, \quad (2.13)$$

or

$$V_i = \frac{W}{2VS_d\rho}, \quad (2.14)$$

where ρ is the air density. Assuming that the induced air velocity V_i is small in comparison with the flight speed V , the induced power is

$$P_{ind} = W \cdot V_i = \frac{W^2}{2VS_d\rho}, \quad (2.15)$$

However, at very low flight speed V , and in hovering flight ($V=0$), the induced power is calculated by:

$$P_{ind-hov} = \sqrt{\frac{W^3}{2\rho S_d}}. \quad (2.16)$$

For relations (2.6) and (2.7), there were used ideal assumptions, where S_d is the area of a circle with a diameter equal to the wing span, and that the air contained within the disk passes through it at exactly V_i , the air induced speed, whereas that outside air is unaccelerated. For practical values of P_{ind} it is necessary to introduce a correction factor k , therefore

$$P_{ind} = k \cdot \frac{W^2}{2VS_d\rho}, \quad (2.15a)$$

and

$$P_{ind \cdot hov} = k \cdot \sqrt{\frac{W^3}{2\rho S_d}}, \quad (2.16a)$$

where the disc area is taken to be

$$S_d = \frac{1}{4} \pi b^2. \quad (2.17)$$

For airplanes wings and helicopters rotor the correction factor is $k = 1.1 - 1.2$, but there are no reliable experimental determinations for animal wings. Usually in earlier theories, there were suggested values of $k = 1$ and $k = 1.43$, but lately they were considered unrealistic. Pennycuik, 1989, suggested an estimate of the induced power factor of $k = 1.2$.

Power Curve for the ideal flyer – Neglecting the inertial and profile powers, the power required to fly for a flyer with a streamlined body supported by an ideal actuator disk is the sum of the induced and parasite power

$$P_{\Sigma} = P_{par} + P_{ind} = \frac{1}{2} \rho V^3 A + 2.4 \frac{W^2}{V \pi b^2 \rho}, \quad (2.18)$$

It could be seen in Figure 2.16 that the curve is U-shaped, having a minimum at minimum power speed, $V_{mp}=4.2$ [m/s] - for bat *Plecotus auritus*, because there is plenty of air rushing past at high speeds, so that a large force can be produced without having to do much work on the air. The existence of a minimum power speed at which flight is less strenuous than at either faster or slower speeds, is characteristic of any animal or machine that flies by imparting downward momentum to the air. At this minimum speed, the total power required is the absolute minimum power $P_{am}=0.022$ [W], for bat *Plecotus auritus*. The total power required to fly, P_{Σ} , is the sum of the induced power, P_{ind} , and the parasite power, P_{par} .

Figure 2.16: Power curve for a bat dragless wing of *Plecotus auritus* (mass $m = 0.009$ kg).

At some higher speed, V_{mr} , defined by the point of contact with the curve of a tangent from the origin, the ratio of power to speed is a minimum, and so the distance traveled per unit work done is a maximum. This is the maximum range speed, and the power required to fly at this speed is P_{mr} . Expressions for V_{mp} and P_{am} are derived by Pennycuick, 1969

$$V_{mp} = \frac{0.76k^{0.25}W^{0.5}}{\rho^{0.5}A^{0.25}S_d^{0.25}}, \quad (2.19)$$

$$P_{am} = \frac{0.877k^{0.75}W^{1.5}A^{0.25}}{\rho^{0.5}S_d^{0.75}}, \quad (2.20)$$

Similarly, the speed and power for maximum range are

$$V_{mr} = \frac{k^{0.25}W^{0.5}}{\rho^{0.5}A^{0.25}S_d^{0.25}}, \quad (2.21)$$

$$P_{mr} = \frac{k^{0.75}W^{1.5}A^{0.25}}{\rho^{0.5}S_d^{0.75}}. \quad (2.22)$$

From (2.19) to (2.22) it will result that: $V_{mr} = 1.32V_{mp}$, and $P_{mr} = 1.14P_{am}$.

Profile power (P_{pro}) is the power required to overcome the form and friction drag forces on the wings. It is less easy to understand than the induced or parasite powers, and impossible to calculate with any degree of exactness. Profile power is a portion of the power that has to be supplied by the flight muscles to sweep the wing through its arc from high to low and back again. Just as parasite power depends on the speed at which the air blows over the body, so the profile power depends on the speed at which the air blows over the wing, but this speed is not so easy to define. The relative airspeed of each portion of the wing is due to two main components, the flyer's forward speed, and the relative speed due to flapping. The last one is itself a function of forward speed, because the amplitude and the frequency of flapping are high at very low speeds, then decline to minimum values while approaching the minimum power speed, V_{mp} , then increase again as speed is increased further.

Profile power has to be calculated by dividing the wing into a number of strips, each with its local relative airspeed, taking account of variations of forward speed, and of flapping frequency and amplitude. Then, it is necessary to take account of the profile drag coefficient. About this, the aeronautical research indicates that this is strongly dependent on the angle at which the relative airflow strikes the wing, particularly for strongly cambered wings like those of bats, and especially in flight at very low speeds.

However, the profile power has an interesting property which can be exploited as a simple method of approximation. In hovering, the flyer beats rapidly its wings through a large angle, but the relative airspeed is still quite low, because only the induced velocity supplies the air flowing through the wing disc. Therefore, the profile power starts low, when forward speed is zero, but grows up sharply as the speed increases.

As the forward speed approaches V_{mp} , the component of profile power due to forward speed grows up, but the component due to flapping decreases, since the frequency and amplitude of flapping decline, and so does the profile drag coefficient. So, the profile power stays steady, or even decreases slightly, as the speed increases to V_{mp} , and does not increase appreciably until the speed is well above V_{mp} . Thus, the profile power can be regarded as constant,

independent of the forward speed, and we can estimate its magnitude in terms of its body mass and its wing span. Since the absolute minimum power, P_{am} , depends on the mass and the wing span it was argued by Pennycuick, 1975, that any changes of anatomy that increase P_{am} should also increase P_{pro} by the same factor, or

$$P_{pro} = X_l P_{am}, \quad (2.23)$$

where X_l is the profile power ratio and for birds and bats its value is 1.2 (Pennycuick, 1989). The preliminary estimate of the power required to fly at minimum power speed, V_{mp} , becomes

$$P_{min} = (1 + X_l) P_{am}, \quad (2.24)$$

Inertial power (P_{acc}), is the work needed to accelerate and to decelerate the wings at each stroke, that is, to oscillate the wings. The inertial power depends on the moment of inertia I of the wing and the wingbeat frequency, f_w :

$$P_{acc} = \frac{I\omega}{t} = 8\pi^2 I f_w^3 \gamma^2 \propto b^2, \quad (2.25)$$

where ω is the angular velocity of the wings, and γ is the positional angle of the wings (Norberg, 1996). The shorter and lighter wings have a reduced the inertial power, since the moment of inertia depends on wing mass and length.

The total mechanical (output) power required to fly is:

$$P = P_{par} + P_{ind} + P_{pro} + P_{acc}, \quad (2.26)$$

In addition to the mechanical costs are the costs of internal body functions P_b (resting metabolic rate) and the costs for circulation of the blood and ventilation of the lungs connected with flight activity, which are about 5% each of the total power for other purposes (Tucker, 1973). Most of the biologists are using this formulation for power calculation. Figure 2.17 represents a summary of the previous analytical model on energy consumption for natural flyer. The energetic cost of flight per gram of body weight shows that in

comparison with the hummingbird and dragonfly wing, the bat wing is requiring a lower power to fly.

Figure 2.17: Comparison of the total mechanical power required to fly.

2.2.3. Kinematic of Flight for Hummingbird

As the smallest birds, hummingbirds are the only birds capable of prolonged hovering. They are unique in that both forward and backward strokes generate lift during hovering, and they are thus capable of extended hovering to feed on high energy nectar. Other birds get all of their lift from the downstroke, and insects manage to get equal lift from both up and down beats, but the hummingbird lies somewhere in between. It gets about 75% of its lift from downstroke and 25% from the upwards beat (Figure 2.18). Although hummingbirds do flap their wings up and down in relation to their body, they tend to hold their bodies upright so that their wings flap sideways in the air. To gain lift with each stroke the birds partially invert their wings, so that the aerofoil points in the right direction. Their flight looks a little like the arm and hand movements used by a swimmer when treading water, albeit it at a much faster pace (Warrick et al., 2005).

Insects attain the same lift with both strokes because their wings actually turn inside out. A hummingbird, with wings of bone and feathers, isn't quite so flexible but they are still very efficient. Ordinary birds can articulate their wings folding and bending their wrists and elbows. Hummingbirds, however cannot articulate their wings at elbow and wrist, but they are able to rotate them in all directions at the shoulder joint, due to their unique ball-and-socket shoulder joint (Figure 2.19) (Ritchison, 2006). Their wings are moving differently from the other birds at shoulder joint.

Figure 2.18: The mechanism of gaining lift from downstroke and upstroke for different flyers. (Credit: Nicolle Rager Fuller, NSF)

Figure 2.19: Wing bone structure of the hummingbird. [Ritchison06].

During forward flight, the wings move up and down in a paddling motion (Figure 2.20). Unlike other birds, hummingbirds can beat their wings up to 200 times per second. The top speed for hummingbird is about 30 mph, 60 mph when diving. During stationary hovering flight, the wings are moving through a large angle in an approximately horizontal stroke

plane in a figure-of-eight motion with symmetrical half-strokes (Figures 2.21 and 2.22) (Stolpe and Zimmer, 1939, Greenewalt, 1960). For the hovering flight, the wings paddle forward and back, roughly in the shape of a figure eight. The sequence of wing movement in hovering are: the top edge of the wing always leads the bottom edge, and at the same time, the wing is curved slightly upward, creating a downward thrust of air. If the wings are tilted, this thrust is used to steer the hover in the desired direction (Long, 1997).

Figure 2.20: Forward flight: the wings move up and down in a paddling motion, with a frequency up to 200 Hz (Stolpe and Zimmer, 1939).

Figure 2.21: Hovering flight (Stolpe and Zimmer, 1939).

When hovering, their wings move from front to back 30-70 times per second. The smaller the hummingbird is, the more wing-beats per second. Another notable idea is that they are the only birds capable of sustained hovering and backward flight and they alone can probe flowers without perching (Figure 2.21). The hummingbird wing is free to rotate in all directions at the shoulder. The angle of attack is attained very fast at the beginning of either

stroke and remains almost constant until the wing reaches the end of its travel. Weis and Fogh, 1972, calculated the mean angle of attack to be 23° during both strokes of the wingbeat cycle. The pattern of the wing motion is very close to perfectly sinusoidal.

Figure 2.22: The sequence of wing movement in hovering (Long, 1997).

2.2.4. Kinematic of Flight for Dragonfly and Damselfly

Dragonflies are fantastic to watch but difficult to catch. Dragonflies are capable of long-time hovering, fast forward flight and quick maneuver. Dragonfly flight has fascinated scientists for most of the last century. These insects are large, colorful and striking, and thus readily capture one's attention as they fly past. Damselflies are often confused with dragonflies, but the two insects are distinct: most damselflies at rest hold their wings together above the body, whereas dragonflies at rest hold them out, either horizontally or slightly down and forward. Many scientists studied their flight and made comparisons between the two species (Figure 2.23).

Dragonflies however are unable to use the clap and fling mechanism, and so they must rely on other unsteady lift mechanisms. Ellington, 1984, suggests that an isolated rotation of the wings, coupled with flexion of the wing, may generate additional lift in a similar way to the clap and fling motion. This combined motion causes the wing to rotate about its trailing edge, which should produce a leading-edge vortex of the correct sense for lift on subsequent

translation. In their motion, the wings change from being cambered in one direction, through being flat, to being cambered in the other direction, with a resultant change in wing chord.

Figure 2.23: Side views of a dragonfly *Anax parthenope julius*, (a) and damselfly *Ceriagrion melanurum*, (b), with the wings folded. Note that they are not shown to the same scale, the dragonfly being larger (Sato and Azuma, 1997).

Figure 2.24 shows a side view of a dragonfly *Calopteryx splendens* with the respective wingtip positions during a wing stroke. Points for the forewing tip are marked as blue circles, while points for the hindwing tip are marked as red diamonds. The stroke planes are indicated by the pairs of colored arrows and pass through their respective wingbases, each denoted by a cross. The body is shown at the mean body angle χ and is also drawn to scale. The wingtip path is given by the colored symbols. Black arrows show the direction of travel for the wingtips.

Figure 2.24: The analyzed wingbeats for *Sympetrum sanguineum* (Wakeling, 1996).

An analysis of the data from Table 2.5 indicates that damselflies are characterized by lower wingbeat frequencies, higher stroke and amplitudes than dragonflies. Despite the size

similarity for the two species, the damselfly flows with the mean wingbeat frequency f of 20 Hz, for both the fore and hindwings, that is half of the frequency for the dragonfly wingbeats. Flight velocities are greater for the dragonfly than for the damselfly. The damselfly could perform a clap and fling, and the proximity to which the wings approached each other during this maneuver correlated with the total force produced during the wing stroke. The dragonfly beat its wings with a set inclination of the stroke planes with respect to the longitudinal body axis; the damselfly, in contrast, showed a greater variation in this angle (Wakeling, 1996).

Table 2.5: Mean morphological data and flight parameters for some species of dragonflies

Variable	Sympetrum sanguineum ¹		Calopteryx splendens (Damselfly) ¹		Anax parthenope Julius ²	
Body mass [mg]	111-139		91 - 119		790	
Mean thrust [mN]	1.93		1.34			
Wingspan, b, [cm]					Forewing 9.9 - 10.6	Hindwing 10.1 - 10.4
Combined area wing [cm ²]	2.9-3.6		3.9 - 4.3		19.9 - 21.8	
Aspect ratio AR					Forewing 11.2 - 11.6	Hindwing 8.8 - 9.4
Wing length, R [mm]	Forewing 27.8-29.4	Hindwing 26.1-28.5	Forewing 29.7 - 30.4	Hindwing 28.7-29.4		
Wingbeat frequency [Hz]	38.7	39.2	19.9	20.3		
Stroke amplitude [°]	90.5±5	101.6±3.9	120±7.5	121±7		
Wing area [cm ²]	3-3.6					
Flight velocity, V [m/s]	1.31		0.94			
Mechanical power, [W]	0.015		0.01			

1 – Data from (Wakeling, 1996)

2 – Data from (Okamoto, 1996)

2.2.5. Kinematic of Flight for Bat

The kinematic of *Plecotus auritus* in slow horizontal flight, at $v=2.35$ m/s, was thoroughly studied in Norberg, 1976. The **downstroke** of the wings begins with the wings raised well above the horizontal (with an angle of about 49.4° above the horizontal), and extended

slightly back, behind the center of gravity (Figure 2.26). At the start of the downstroke the wings are fully extended and are at a fairly high angle of attack, and the propatagium is stretched taut. At the start, the corresponding positional angle $\phi_{downstroke}$ of the long wing-axis in the stroke plane is 153.5° (Figure 2.25). The wing then sweeps downwards and forwards fully extended and moves essentially in one plane, tilted 58° to the horizontal.

Figure 2.25: Wing-stroke plane with some characteristic angles.

As the wings are pulled rapidly downward the digit membrane twists, its trailing edge becomes higher than the leading edge. During the remaining time of the downstroke, the digit membrane remains twisted by the force of the air pressure and its pitch is progressively greater distally (Figure 2.26, c). Due to its elasticity, the membrane between digits four and five is bulking upward producing some thrust, yet because of its greater pitch the membrane between digits three and four develops most of the thrust. The amount of lift produced by the chiropatagium is difficult to evaluate. High speed photographs suggest that together with providing most of the thrust developed during the downstroke, the chiropatagium also produces some lift (Vaughan, 1970). However, the position of the hind limbs, the rigidity of the fifth metacarpal, and the partial flexion of the phalanges of the fifth digit, maintain the proximal segment of the wing, during the downstroke, at an appropriate angle of attack for the production of lift. This is the moment when the structures that brace the fifth metacarpal are of greatest importance. When the wings are approximately horizontal their leading edges are nearly at right angles to the long axis of the body, but toward the end of the downstroke the wings make sharply forward angles, anterior to the center of gravity (Figure 2.26, c).

Otherwise, the wing is fully extended throughout the downstroke, and the leading edge forms almost a straight line.

(a) Beginning of the downstroke. The tail and feet are held straight backwards.

(b) Middle of the downstroke. The twisting of the wings is clearly seen in the upper photograph.

(c) Later part of the downstroke. The wings are sharply cambered, and the tail membrane is fully lowered.

(d) Beginning of the upstroke. The elbows and wrists are slightly flexed. The camber is still pronounced.

(e) Later part of the upstroke. The feet are raised which reduces the camber of the proximal part of the wings. The middle part is still cambered, but the wing tips are momentarily inverted.

Figure 2.26: Long-eared bat *Plecotus auritus* in slow horizontal flight (Norberg, 1976).

There is a similar pattern of wing beat between bats and birds. During the downstroke, the wings are fully extended and sweep downwards and forwards until the tips are ahead of the bat's nose. The leading edge is tilted down during this phase, particularly towards the tip. The downstroke produces lift and forward propulsion, and since the aerodynamic center of pressure lies behind the skeleton, the bones experience considerable twisting forces (Swartz, 1992).

The **upstroke** starts with a slight flexion at the elbow and wrist, but the phalanges, when the wing has reached the positional angle $\phi_{upstroke} = 62.8^\circ$ (Figure 2.26, d). Raising and flexion of the humerus causes partially the automatic flexion of the forearm and of the digits. The wrist begins to rise while the wing tip and trailing edge are still moving downwards. The whole wing is then brought upwards and backwards relative to the body. The hand wing is fully extended during the entire upstroke (Figure 2.26, e).

Because of the high angle of attack of both the chiropatagium and the plagiopatagium, the force of the airstream seems to help for raising the wings during the upstroke. The partial flexion of the wing reduces its area and thus the amount of drag it develops. The wing remains partially flexed and at a high angle of attack throughout the upstroke, but tends to be most fully flexed at the middle of the upstroke. The distal segment, chiropatagium, appears to produce thrust during the downstroke largely due to its specialized trailing edge. The leading edge of the chiropatagium, formed by digits two and three, is fairly rigid, while the elasticity of the membranes between digits three, four, and five, and the slight flexibility of the distal part of the fourth digit, allow the trailing edge to yield to the force of the airstream. During the downstroke, the chiropatagium looks like a propeller with the pitch becoming progressively greater in the distal part.

The tendency for turbulence over the highly cambered wing of bats at high angles of attack is reduced by the bony framework of the wing. It is possible that the irregularities in the surface, particularly those produced by the humerus, radius, and second and third digits, increase the efficiency of the bat wing. Schlichting, 1960, shows that certain surface irregularities change the airflow in such a way as to reduce the tendency for turbulent

breakaway. In order to overcome the inertial forces at the end of a stroke of the wing beat, the wings of the bats are lightweight, and at the same time, their structural skeletal components are able to withstand the buckling forces generated by air pressure under the wing during the downstroke. These buckling forces are focused at the elbow, wrist and finger joints, and the joint strength is accomplished locking the joint motion to those planes, horizontal in most cases, that are perpendicular to the buckling forces. The elbow joint is designed with deep grooves and bony flanges that the joint opens and closes in the horizontal plane.

2.3. Summary of MAV and of morphological and flight parameters for small natural flyers

With a wingspan of about 15 cm and a flight speed of a few meters per second, the MAVs experience the same low Reynolds number of $10^4 - 10^5$ of flight conditions as the small natural flyers. In this flow regime, the scaled down airplane-like MAVs with rigid wings experience a dramatically drop in aerodynamic performance compared to their models from civil and military aircraft, while flexible flapping wings gain efficiency as a propulsion method (Ho et al., 2003). Also, an improvement is made to the efficiency of a rigid flapping wing platform using a flexible wing with articulated joints having, therefore a tendency to approach the efficiency of natural flyers.

With respect to the insect flight, i.e. dragonfly, damselfly and butterfly, the mechanisms of flapping flight seem to be very efficient at the insects scale. Obviously, for designing a MAV is expected from it to sustain more than the weight of a dragonfly which is less than 1g for a wing length of 5 cm. Maintaining the same wing span for MAV and expecting from it to sustain 10g, the wingbeat frequency should increase significantly. For example, for hovering flight, Ellington and Usherwood, 2001, observed that the lift is proportional to $f^2 R^4$ where f is the wingbeat frequency and R is the wing length. It results, therefore that maintaining the same wing length for MAV and expecting to sustain 10g, the frequency required is around 100 Hz, whereas the dragonfly hovers at 40 Hz. As a consequence, scaling up the insect wing

and using it to build a 10g MAV is unsatisfactory in a design with SMA as actuators, due to the increase in actuation frequency.

Hummingbirds have a higher absolute value of wing loading and so they are coming after butterflies and bats with respect to maneuverability. They can hover and are the only known species between natural flyers that can fly backwards, but their need for a high wingbeat frequency to generate lift makes them unsuitable to be actuated with SMA wires.

The butterflies have the least wing loading, which makes them to be very maneuverable and also needing a lower wingbeat frequency (7 – 12 Hz) to maintain the flight. For a MAV of 2g with a wingspan of 15cm the butterfly wing will be a very good candidate to be actuated with SMA wires.

This analysis showed that the bat wing is a suitable match for a 10g MAV with SMA actuation considering their wingbeat frequency of about 10 Hz. The bat wing is unique among flyers limbs in anatomical design and mechanical function, enabling these fliers to perform easily complex maneuvers. Since they are thin airfoils of high camber, they are very effective in producing high lift at low speeds. The relative low specific wingspans in bats allow them to have a maneuverable flight even though this makes a larger drag for high velocity flight. This maneuverability makes them suitable for the expected missions of BATMAV, mentioned earlier in introduction. The next chapters will study the kinematic of flight for the long-eared bat, *Plecotus auritus*, which is a low-speed flier, yet very good in maneuvering, and hovers easily.

CHAPTER 3

KINEMATIC OF FLIGHT AND FLIGHT MUSCLES FOR SMALL BATS

3.1. Glossary

Since a large part of terminology has a biological provenience, it is useful from an engineering point of view to introduce and explain its significance. Figure 3.1 shows the most frequent terms used for a bat wing. These terms are:

- ***Patagium*** is the wing membrane having a thickness of about 0.03mm. It incorporates elastic fibers and bundles of muscle fibers.
- ***Plagiopatagium*** is the large portion of the wing (between body and fifth digit) (Figure 3.1). This is a lift-generating section, and its camber is controlled by flexing the body axis and/or the fifth digit.

Figure 3.1: The bat wing structure with used biological terminology. MCP5 is the metacarpal of the fifth digit.

- ***Propatagium*** is the small portion between shoulder, elbow and wrist, and it is used especially to produce lift.
- ***Uropatagium*** is the membrane between legs and tail and helps to increase the effective lifting area of the wing. It operates in synchrony with the plagiopatagium, and is also used as an airbrake.
- ***Chiropatagium*** is the digit membrane and is especially a propelling or thrust generating portion. Its camber can be changed by flexing the digits.

3.2. Flight muscles in bats

Natural fliers use the pectoral muscle as the main adductor or depressor which means that draws the wing toward the median line of the body, the downstroke, and usually as a pronator or nose-down rotator of the wing, so that the wing faces backwards or downwards. Norberg, 1998, studied the direction of pull of the main flight muscles in bats, Figures 3.2 – 3.4. The main upstroke muscles are the *spinodeltoideus* and the *acromiodeltoideus*, the *trapezius* group and the long and lateral head of *triceps brachii* (Figure 3.4). The trapezius muscles move the scapula toward the vertebral column, and so they are acting as indirect wing elevators. There are also several bi-functional muscles, controlling the humeral orientation and stabilizing the shoulder joint.

3.2.1. The downstroke generator muscles

The propulsion stroke is the downstroke of the wings, and the largest muscles located on the chest and upper part of the humerus are those causing this action. During the downstroke, the *pectoralis* and the *serratus anterior* are the main adductors of the wings, whereas the *clavodeltoideus* mainly extends the humerus pronated by the *latissimus dorsi* (Figures 3.2 – 3.3). Four large muscles act on the humerus during the downstroke:

1. M. *pectoralis* which is attached at clavicle and sternum and is acting on the proximal humerus. In bats this large sheet of muscle is divided into two parts that represent most important groups of muscles controlling the downstroke of the wings:

- *M. Pectoralis* – anterior division that originates on the clavicle. This muscle pulls the humerus downward and forward and rotates it by tilting the pectoral ridge. It originates from proximal three-quarters of ventral surface of clavicle (Figure 3.4).
- *M. Pectoralis* – posterior division which originates on the sternum. The posterior division of the *pectoralis* helps produce the downstroke of the wing by drawing the humerus toward the median line of the body and pulling the leading edge of the wing downward. This muscle can control the downstroke of the wing through a considerable range of planes.

Figure 3.2: Direction of pull of the flight muscles – anterior view of the left shoulder region, showing the direction of pull of muscles moving the arm (Norberg, 1998).

During the wingbeat cycle, both divisions of this muscle work together, their action not only draws the humerus toward the median line of the body, but pulls it well forward, spreading the wing. Since the insertion of the *pectoralis* muscle is anterior to the long axis of the humerus, Figures 3.3 and 3.4, this muscle acts as a rotator of the humerus and in this way controls the angle of attack and the rotational stability of the wing by operating against the

counter rotational action of the *biceps branchii*. Due to the variety of directions from which the fibers of the *pectoralis* pull on the humerus and the extensiveness of their insertion, the action of this muscle alone imparts considerable rotational stability to the humerus.

2. *M. clavodeltoideus* is anchored at clavicle and is pulling on the proximal humerus making the elbow to move away from the body and so, is helping the wing to be extended during the downstroke.
3. *M. serratus anterior*, attached on the broad band from mid-section ribs one to four and is pulling on the anterior middle portion of the scapula.
4. *M. subscapularis*, which is anchored on the body at the ventral surface of scapula and is pulling on the proximal humerus.

Figure 3.3: Direction of pull of the flight muscles powering the downstroke – ventral view of the left shoulder region, showing the direction of pull of downstroke muscles acting on the clavicle, and the humerus (Norberg, 1998).

The unique attachments of these muscles enable them to help in the downstroke motion of the wing. In comparison with the terrestrial mammals, the greater tuberoses of bat humerus,

due to a series of particularities of the *scapulo-humeral* articulation, locks against the scapula at the top of the upstroke of the wing. This locking transfers the work of stopping the upstroke to this muscle, which is done by anchoring the lateral edge of the scapula, and by pulling this edge of the scapula this muscle moves the locked humerus downward and begins the downstroke.

3.2.2. Muscles of the upstroke motion

The muscles that lift the wing through the recovery stroke are located on the upper part of the back. These muscles are smaller in overall size than those for downstroke and are acting directly on the scapula and indirectly on the humerus. Three muscles or muscle group are involved in the wing upstroke:

1. The *trapezius* muscle group is composed of *acromiotrapezius* and *spinotrapezius* muscles (Figure 3.4).
 - The *acromiotrapezius*, (*acromion* is the outer upper point of shoulder blade, or scapula) pulls the clavicle and scapula, (scapula is either of two flat, triangular bones in the back of the shoulders of vertebrates), and the tips of the vertebral border of lower part of the scapula by acting in the upstroke of the wing when it braces the scapula against the pull of the *deltoideus*, *supraspinatus* and *infraspinatus* muscles.
 - The *spinotrapezius* pulls the scapula and tips of the vertebral border, and its function in the wingbeat cycle is similar to that of the *acromiotrapezius* muscle.
2. The *Costo-spino-scapular* muscle group which is mainly formed from two muscles:
 - *M. levator scapulae* originates from cervical vertebrae four to seven, by four large slips, and its action is to draw the middle front border of the scapula and together with the trapezius and *rhomboideus* muscle to brace the scapula during the upstroke of the wing (Figure 3.4).
 - *M. rhomboideus* is attached on the thoracic vertebrae one to seven, is pulling on the medial border of scapula, moving this bone. It pulls the medial scapula and together

with the *trapezius* muscles and with the anterior division of the *serratus anterior*, helps to control the upstroke of the wing (Figure 3.4).

3. The Deltoid muscle group. *M. acromiodeltoideus* is acting on the lateral surface of pectoral ridge of humerus, and so, it elevates, rotates and flexes the humerus. Together with the *spinodeltoideus*, *infraspinatus*, *trapezius* and *rhomboideus* muscles the *acromiodeltoideus* controls the upstroke, raising the humerus and rotating it such that the leading edge of the wing is tipped upward, and therefore they cause a rotation of the entire wing and change its angle of attack. The angle of attack is the angle of the chord line of the airfoil with the plane of motion.

Figure 3.4: Dorsal view of the right shoulder region, showing the direction of pull of upstroke muscles acting on the scapula and the humerus (Norberg, 1998).

High speed photographs of bats in flight show that during upstroke, the wing is raised and partially flexed and maintains a fairly high angle of attack which makes the airstream to help

during the upstroke and the wing probably produces some lift during the upstroke (Figure 3.5). The control of the angle of attack and the rotational stability of the wing during the upstroke are of basic aerodynamic importance. *Deltoideus* and *infraspinatus* muscles also seem to affect this control serving as counter-rotator against the *latissimus dorsi* and *teres major* muscles.

Figure 3.5: Cross section through the proximal segment of the *Miotis evotis* wing showing the angle of attack, α .

3.2.3. The muscles controlling the flight membranes

The proximal segment of the wing, *plagiopatagium* and *propatagium*, produces most of the lift, and the distal segment, *chiroptagium*, produces most of the thrust developed by the wingbeat cycle (Figure 3.6). The proximal segment is maintained at an appropriate camber and angle of attack for the production of lift throughout the wing beat cycle. The degree of curvature of the fifth digit has an important role in determining and maintaining the angle of attack and the camber of this segment. By retaining its curvature and angle of attack throughout the wing beat cycle, the fifth digit partly controls the lift produced by the proximal segment (Vaughan, 1970).

When the bat is at rest, its wings are folded in an accordion shape-like. Then, at the beginning of the flight, a rapid extension of the fingers of the wings occurs, extension that is generated by the contraction of a single muscle, the *supraspinatus*. Neuweiler, 2000, shows

the fact that one section of the triceps, the muscle that extends the lower arm, is not attached to the upper arm at any point as it is in other mammals, but instead is attached completely to the shoulder blade. The main groups of muscles that are located in the wing structure are:

- *M. occipito – pollicalis*. This muscle pulls the *propatagium* between cranium and wrist, thereby increasing the area of the proximal segment of the wing and improving its airfoil (Figure 3.7).
- *M. coraco – cutaneus*, has the origin from distal part of medial ridge of humerus and its insertion into armpit part of slanting zone of the membrane (the '*plagiopatagium*') (Figure 3.7). This muscle attaches distally to networks of elastic fibers and by anchoring these to the armpit braces and helps to maintain tightly stretched the proximal part of the *plagiopatagium* during flight.
- *M. humeropatagialis* originates with a thin layer of connective tissue from the middle surface of the humerus bone and from postero-medial surface of base of ulna (Figure 3.7). This muscle tightens and braces the distal part of the *plagiopatagium*.
- *M. tensor plagiopatagii* anchors and braces the trailing edge of the *plagiopatagium* and the part of this membrane that attaches to the shank (Figure 3.6).

Figure 3.6: Frontal view of the left wing of *Eumops perotis*, showing the muscles and part of the system of elastic fibers that brace the wing membranes (Vaughan, 1970).

The mechanism that extends and folds the wing during the flapping motion is showed in Figures 3.7 and 3.8. This mechanism originates on the shoulder blade and on the upper arm, humerus bone. The muscles that extend the forearm and the finger part of the wing are triceps and extensor carpi radialis and the muscles that are folding the wing during upstroke to reduce drag are biceps and flexor carpi ulnaris.

WING EXTENDED

WING FLEXED

Figure 3.7: Muscles that extends and fold the wing (Vaughan, 1970). The names of muscles that extend and flex the wing are boldfaced.

Figure 3.8 (a) shows the skeletomuscular force lever system which involves *musculus extensor carpi radialis longus* that is pulling the leading-edge of the second digit forward. Since this muscle controls the leading edge of the distal segment of the wing, it is recommended to be introduced into the simplified engineering actuation model. This muscle

passes along the anterior side of the forearm, and its tendon passes anterior to the carpal bones at a distance from the fulcrum of the second metacarpal. The trapezium of the *carpus* projects dorsally and prevents the tendon from sliding posteriorly when the muscle contracts. Another similar force lever system is showed in Figure 3.8 (b), and occurs in the fifth digit. The contraction of the *musculus abductor digiti quinti* pulls the fifth metacarpal ventrally, maintaining the chordwise camber of the wing during the downstroke for efficient lift production.

Figure 3.8: The flexion muscular mechanism for the finger part of the wing: a) Skeletomuscular force lever system of the bat wrist, b) The metacarpal force lever system of the fifth digit (Norberg, 1970).

3.3. Considerations of aerodynamics of bat flight

Bats, in contrast to birds, are able to vary the camber of their wings, by flexing the phalanges of the fifth digit, and by lowering the hind limbs. In this way the trailing edge of the plagiopatagium is curved downward producing an effect comparable to that caused by lowering the flaps on the wings of an airplane. These movements causes the wings to produce a greater lift at low speeds, allowing the wings to operate effectively at a greater variety of flight velocities than that wings with a fixed camber, like in birds.

The aerodynamic characteristics of the bat wing are also influenced by the shape of the wing projection in a horizontal plane. The elliptical shape, characteristic of many small bats and birds, is efficient at low speeds when flight is normally near vegetation or near the surface of

the ground, where a high maneuverability is necessary to avoid obstacles. However, this type of wing loses relatively more lift due to the turbulence of the wing tip vortex than the wings with a longer and narrower shape.

In bats the wings beat almost constantly during flight and developing thrust rather than lift seems to be the most important function of the distal segment of the wing. Although the wingbeat cycle is similar in bats and birds, some major functional contrasts result from the different kinds of wing surfaces involved. In birds the surfaces are formed by feathers and the slots between primary feathers increase the aerodynamic efficiency at the wing tip by reducing the wing top vortex. When the bird wing is partly folded, particularly during the upstroke, the overlapping system of feathers makes a smaller surface area but still retains its rigidity. For bat wing none of the aerodynamic refinements at the wing tip allowed by feathers are possible. However, a folded bat wing maintains its rigidity by a system of muscle and elastic fibers in the membranes (Figure 3.9).

Figure 3. 9: Shape of wing and pattern of some of the elastic fibers in *Myotis evotis* (Vaughan, 1970).

3.4. Summary of the flight muscles in bats and a proposed model for flight muscles of BATMAV

The above analysis of the flight muscles shows a large complexity of this apparatus. From an engineering point of view, a simplification of this complexity is recommended. Figure 3.10

shows a way to model the flight muscles of a bat wing using SMA wires – Nitinol wires with a diameter of 50 μm . Also the joints are modeled using the superelastic SMA wires with a diameter of 140 μm .

Figure 3.10: Modeling joints and flight muscles of the bat wing: super-elastic SMA wires – blue – are used to link the bones, being well suited to model even a complex joint such as the wrist, (details A and B). The muscles are modeled by SMA actuator wires– red.

Figure 3.11: Flexion of the upper arm, another DOF of the shoulder joint following the DOF of flapping motion.

Modeling the muscles that power the downstroke and the upstroke depends of the number of DOF that are considered to be modeled in the shoulder joint. For the simplest case of up and down flapping motion with 1-DOF in the shoulder it could be enough to model the whole group of muscles for downstroke with a single SMA wire and vice versa for the group of muscles for upstroke. As it was previously discussed the pectoralis muscle is having a more significant contribution in powering the active stroke – the downstroke. The complex of muscles powering the upstroke could be modeled with a simplified a solution that works in opposition with pectoralis muscle.

Another DOF of the shoulder joint is the flexion and extension of the upper arm (Figure 3.11). At the beginning of the upstroke the upper arm is flexed and at the end of the upstroke and beginning of the downstroke the upper is extended again. The mechanisms that extend and fold the wing during the flapping motion are helping to increase the wing efficiency by reducing the drag during recovery stroke and therefore they should appear on the engineering actuation model for BATMAV. These mechanisms are working in opposite phases and are formed by the triceps and *extensor carpi radialis* muscles for extension and biceps and *flexor carpi ulnaris* for flexion of the wing. The extension and the flexion of the humerus bone will introduce another DOF in the shoulder joint.

Therefore, the DOFs that are recommended to be modeled in order to power the flapping flight and to improve the efficiency are:

- ***Flapping motion*** which is powered by pectoralis muscle to pull the wing downward, during the downstroke and the trapezius group of muscles during the upstroke to pull the wing upward.
- ***Flexion and extension of the upper arm*** which is done by biceps and triceps muscles.
- ***Flexion and extension of the lower arm and finger part of the wing*** which is executed by extensor carpi radialis and flexor carpi ulnaris.

CHAPTER 4

IMAGE PROCESSING

A primary obstacle in understanding the kinematics of bat flight is the absence of detailed kinematic information at high temporal resolution for the real flyer. Few articles were published with respect to the kinematics of bat flight. The most explicit article with kinematic information, Norberg, 1976, studied the kinematics of horizontal flight of *Plecotus auritus* in slow speed. The bats were filmed and photographed as they were flying horizontally in a net cage of $0.6 \times 0.6 \times 3.5 \text{ m}^3$. The filming section was in the centre of the cage, and measured $0.6 \times 0.6 \times 0.85 \text{ m}$ (Figure 4.1). A mirror tilted with 45° to horizontal and placed under the filming section was used to catch bottom view of the bat flight (Figure 4.2). Lateral, ventral and front (or back) views were obtained from different flights. Front and back views were sometimes obtained from the same flight, when the bat turned in the net tunnel.

Figure 4.1: Filming setup – lateral view: the frontal camera is seeing the projection on the x_0z_0 plane and the profile camera is seeing the projection on the y_0z_0 .

In order to understand the horizontal flight kinematics from an engineering point of view with applications for MAVs we can assign fixed coordinate frames attached to the bat body with their origin in each shoulder. Since the study provides more data for the left wing, we focus our attention on this wing and we apply our conclusion symmetrically to the right wing also. This assumption is not applicable for a turning maneuver in flight, but only for straight

forward flight. A fixed coordinate frame, $x_b y_b z_b$, is attached to the bat body in the shoulder, shown in Figure 4.1, as it follows:

- The axis x_b is in the along the longitudinal axis of the body.
- The axis y_b is the transverse axis – an axis running between the wing tips when the wings are horizontally stretched.
- The z_b axis is the vertical axis which is perpendicular to the other two axes in the right-hand sense.

Therefore, considering a coordinate frame $x_b y_b z_b$ on the left shoulder, we can analyze the trajectories of different points of interest for left wing. Lateral projection, $x_b z_b$ plane – Figure 4.3, is showing trajectories of different points of interest of the forward with a velocity of $v = 2.35$ m/s and a wingbeat frequency of 11.9 Hz. Then, the article presents top and frontal projection of the same points of interest for a flight with a slightly larger velocity of $v = 2.4$ m/s and a wingbeat frequency of 11.8 Hz.

Figure 4.2: Filming setup – frontal view: the projection of the plane $x_b y_b$ reflected in the mirror is seen also by the profile camera.

As it could be seen in the Figures 4.1 and 4.2, the three coordinates are redundant and each is seen in two images:

- x_b coordinate – in bottom and profile view,
- y_b coordinate – in bottom and frontal view,
- z_b coordinate – in frontal and profile view.

A comparison between the data of each coordinate from different views is helping to find accurate trajectories and coordinate time variation along the wingbeat cycle. This variation is used in the next chapter to solve the inverse kinematic of the wing (Figures 4.3 – 4.6).

Figure 4.3: Profile view of wing points trajectories. The coordinates x_b and z_b are seen in this projection. The bat flew with a velocity of $v = 2.35$ m/s and a stroke frequency of 11.9 Hz.

[Norberg76] presented a lateral view of the wing trajectories for a horizontal flight of *Plecotus auritus* bat with a velocity of 2.35 m/s and a wing stroke frequency of 11.9 Hz, but presented for the same study a profile and a bottom view for a forward flight with a slightly faster velocity of 2.4 m/s with a wing stroke frequency of 11.8 Hz. This would introduce errors in the coordinates of different points of interest like wrist, wing tip, etc.

Figure 4.4: Back view of the wing movements to show the trajectories of the digit tips of the wing. The bat flew with a velocity of $v = 2.4$ m/s and a stroke frequency of 11.8 Hz, slightly different than the flight from the Figure 4.3.

Figure 4.5: Bottom view of the wing movements for a flight with $v = 2.4$ m/s and a stroke frequency of 11.8 Hz, slightly different than the flight from the Figure 4.3.

From Figure 4.6 it is obvious that the direction of flight was slightly rotated about z_b axis in a clockwise direction. This and other unknown aspects of the experimental design of data recording contributed to errors and discrepancies between the same coordinate seen in different views, in Figure 4.7.

Figure 4.6: Wingbeat cycle – the bat did not fly straight to the frontal camera and perpendicular to the profile camera.

Figure 4.7: Comparison of z coordinate between the views of the frontal (after the bat had turned away from the camera) and profile cameras. The plot shows that the profile camera sees just a fraction what frontal camera sees.

Since there are many uncertainties about the experimental design, the average of the coordinate values is recommended as a solution to diminish these errors. Using these averages and a MATLAB script, the wrist trajectory is presented in the 3D plot from Figure

4.8. Similarly, the wingtip trajectory is shown in the 3D plot in Figure 4.9. These average coordinates for wrist and wing tip are used in the next chapter with respect to the direct and inverse kinematics of the wing. Using these averages from the data provided by Norberg, 1976, for *Plecotus auritus* bat in slow flight, the wrist trajectory is plotted in Figure 4.8. The wrist trajectory of *Plecotus auritus* bat in slow flight has an elliptic shape. For a velocity of 2.35 m/s with a frequency of 11.9 Hz, *Plecotus auritus* bat is spanning its wrist from about $y_b = 20$ mm up to $y_b = 60$ mm from the shoulder body attached coordinate frame, Figure. At the beginning of the downstroke the wrist has an elevation of about $z_b = 40$ mm, see lateral projection on the $x_b z_b$ plane, and is lowered to about $z_b = -15$ mm. Also, at the beginning of the downstroke the wrist is approximately above the shoulder of the bat, $x_b \approx 0$, and during the downstroke it is moving forward to about $x_b = 30$ mm relative to the shoulder.

Figure 4.8: Wrist trajectory using the average of wrist coordinates from Norberg, 1976.

Figure 4.9: Trajectory of the wingtip and its views using the average of wingtip coordinates (Norberg, 1976).

CHAPTER 5

KINEMATIC MODEL OF FLAPPING WING

5.1. Introduction

Similar to the human hand, the bat wing is a complex structure having multiple DOF for shoulder and wrist, each of them with 3-DOF. The whole kinematic chain has six joints from shoulder up to the tip of each digit with a total of 11-DOF. Figure 5.1 presents an engineering model of the bat wing, where some of the joints were are showed in detail. From an engineering point of view a simplification of the kinematic chain for each digit is recommendable.

Figure 5.1: Engineering model of kinematic structure of bat wing.

A simplest kinematic structure of the wing could be to consider the wing as being rigid and hinged to the body through a 1-DOF shoulder joint. In other words, the whole wing is seen as a beam articulated in the shoulder joint to the body of the bat, Figure 5.2. After a first kinematic analysis of the 1-DOF case, a second DOF will be introduced: the elbow joint. Then, as a third iteration of the kinematic analysis, will be studied the wing with 3 DOF:

shoulder joint, elbow joint and wrist joint, each of them with one DOF. This iterative process of the wing kinematics has two advantages: shows how much the each simplified model can reproduce from the flapping trajectories of the natural bat, and in the same time introduces gradually the analytical model of the direct and inverse kinematics used in this analysis.

Figure 5.2: Modeling the bat wing: a) as a rigid beam; b) The stroke plane of *Plecotus auritus*, (Norberg, 1976).

Assuming just one DOF for the shoulder joint is inspired from an almost in-plane motion during the entire stroke of the bat wing. Norberg, 1976, shows that for *Plecotus auritus* in slow horizontal flight with 2.35 m/s the inclination of the stroke path relative to the horizontal plane varied between 50° and 64° with an average of 57.8°, Figure 5.2 b). Using the kinematic model with one DOF helps to understand the analytical model of the forward and inverse kinematics and set the foundation for more complex models that will be discussed in next sections.

The shoulder joint of the natural bat is a complex joint formed by three bones: scapula, clavicle and humerus bone, with 3-DOF (Figure 5.3). Two of these DOF are contributing

more to the trajectories of the wing during the wing stroke. The swivel arm is the DOF that is generating the flapping motion when the wing is moving from the upper position towards the lower point of its trajectory. The arm flexion is the second DOF of the shoulder and flexing and extending the humerus bone relative to the body such that the extended wing has a maximum area during the downstroke and the flexed configuration of the wing has a minimum area during the upstroke. In this project as a first iteration of the wing kinematic is used just the swivel DOF and the contribution of the arm flexion DOF on the wing kinematic will be analyzed in a future part of this project.

Figure 5.3: Configuration of the shoulder DOFs for horseshoe bat *Rhinolophus ferrumequinum* (pictures after Aldridge, 1986).

5.1.1. Coordinate systems and Denavit-Hartenberg notation

A first coordinate frame is the coordinate frame $x_b y_b z_b$ attached to the body frame in the shoulder joint which was defined in the chapter 4. In order to use a standard notation for all

coordinate frames that will be introduced with each new DOF, the Denavit-Hartenberg notation is adopted. Denavit-Hartenberg notation is widely used in the transformation of coordinate systems of robot mechanisms. It can be used to represent the transformation matrix between coordinate systems of the bone joints for the bat wing. The method is based on the 4×4 matrix representation of rigid body position and orientation. It uses a minimum number of parameters to completely describe the kinematic relationship. Therefore, since the design of BATMAV is adopting a flexible wing having a succession of articulated “bones”, its kinematic structure could use successfully the analytical model used in the kinematics of robot manipulators.

In the Denavit-Hartenberg notation the axes z_{i-1} and z_i of the coordinate frames $x_{i-1}y_{i-1}z_{i-1}$ and $x_iy_iz_i$ are directed along the joint axis specific to that coordinate frame, Figure 5.3, and axis x_{i-1} is directed along the common normal oriented from O_{i-1} toward O_i . Therefore, the axis x_{i-1} will be any time perpendicular on both z_{i-1} and z_i axes. Finally, the axis y_{i-1} is chosen such that the resultant frame $x_{i-1}y_{i-1}z_{i-1}$ forms a right-hand coordinate frame. Therefore, using the Denavit-Hartenberg notation the z_i axes are the first to be selected having directions for revolute joints such that the right-hand rule rotations about them correspond to positive link angle motion. After all of the z_i axes have been identified, the x_{i-1} axes can then be specified so that each x_{i-1} is defined from z_{i-1} to z_i and perpendicular to both, (Wolovich, 1987).

Figure 5.4 shows an arbitrary pair of adjacent links link $i-1$ and link i , and their associated revolute joints $i-1$ and i . The relative location of the two frames can be completely determined by the following four parameters:

- 1 The **link twist**, α_{i-1} , which is the angle measured from axis $i-1$ to axis i in the right-hand sense about the axis, x_{i-1} .
- 2 The **link length**, a_{i-1} . For the two revolute joint axes, $i-1$ and i , in 3D space there is a well-defined measure of distance between them. This distance is measured along a line which is mutually perpendicular to both axes called the **common normal**. This common normal always exists and is unique except when both joint axes are parallel, in which case there are many mutual perpendiculars of equal length. The length of the common normal is one of the parameters used to make the transformation from the

coordinate frame $x_i y_i z_i$ attached to the link i to the coordinate frame $x_{i-1} y_{i-1} z_{i-1}$ attached to the link $i-1$, and is called the **link length**, a_{i-1} .

- 3 The **joint angle**, θ_i , which is the between the x_{i-1} axis and the x_i axis measured about z_i axis in the right-hand sense.
4. The **link offset**, d_i , which is the distance between the origin O_{int} of the intermediate frame and the origin O_i measured along the z_i axis.

Figure 5.4: The Denavit-Hartenberg notation applied to an arbitrary pair of “bones” with revolute joints (Craig, 1989).

For the bat wing the parameters a_i , d_i , and α_{i-1} are constant parameters that are determined by the geometry of each bone:

- a_{i-1} represents the bone length which is constant for any bone of the wing.
- The bone twist α_{i-1} is the twist angle between the two joint axes and usually is 0° or -90° or 90° .
- The bone offset d_i is negligible for most of the bones since they are almost straight, their curvature and thickness is rather of orders of mm.

In order to find the transformation which defines the frame i with respect to frame $i-1$ it is useful to understand the way from frame $i-1$ to frame i :

- 1 Starting from the origin O_{i-1} , the frame $x_{i-1}y_{i-1}z_{i-1}$ is rotating with the link twist angle α_{i-1} about axis x_{i-1} until the axis z_{i-1} coincides with axis z_i .
- 2 The coordinate frame $x_{i-1}y_{i-1}z_{i-1}$ is translating along the axis x_{i-1} with the distance a_{i-1} , the result is the new intermediate frame $x_{int}y_{int}z_{int}$.
- 3 The intermediate frame $x_{int}y_{int}z_{int}$ is rotating with the joint angle θ_i about the axis z_{int} .
- 4 Finally, the intermediate $x_{int}y_{int}z_{int}$ frame is translating with the offset distance d_i along the axis z_i .

Therefore, as a consequence of these transformations, the following matrices can be written:

- The rotation matrix about axis x_{i-1} with the angle α_{i-1} :

$$R_{x_{i-1}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha_{i-1} & -\sin \alpha_{i-1} & 0 \\ 0 & \sin \alpha_{i-1} & \cos \alpha_{i-1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.1)$$

- The translation matrix along axis x_{i-1} with the distance a_{i-1} :

$$T_{x_{i-1}} = \begin{bmatrix} 1 & 0 & 0 & a_{i-1} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.2)$$

- The rotation matrix about the axis z_i with the angle θ_i :

$$R_{z_i} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & 0 \\ \sin \theta_i & \cos \theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.3)$$

- The translation matrix along the axis z_i with the offset distance d_i :

$$T_{z_i} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.4)$$

Finally, the homogenous transformation matrix A_i^{i-1} from the frame $x_i y_i z_i$ to the frame $x_{i-1} y_{i-1} z_{i-1}$ is written using the chaining operation of the matrices (5.1) – (5.4):

$$A_i^{i-1} = R_{x_{i-1}} \cdot T_{x_{i-1}} \cdot R_{z_i} \cdot T_{z_i} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & a_{i-1} \\ \sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -d_i \sin \alpha_{i-1} \\ \sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & d_i \cos \alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.5)$$

The matrix A_i^{i-1} represents the position and orientation of coordinate frame $i-1$ relative to the coordinate i . The first three 3×1 column vectors of this matrix contain the direction cosines of the coordinate axes of frame i relative to the frame $i-1$, while the last 3×1 column vector represents the position of the origin O_i with respect to the frame $i-1$.

5.2. The simplest case: 1-DOF model

Figure 5.5 shows the kinematic structure for the rigid wing with one joint – the shoulder joint – having just 1-DOF. Figure 5.5 A) presents the usual way of representing a revolute joint with 1-DOF and Figure 5.4 B) shows the engineering solution used for the shoulder joint with super-elastic SMA wires for the shoulder joint. There were used two wires of 0.140 mm diameter in order to have an in-plane motion.

The degree of freedom of the shoulder joint is the shoulder swivel θ_I . The fixed coordinate frame $x_0 y_0 z_0$, called the base frame, is attached to the bat body and is introduced to show the inclination of the stroke plane with respect to the frame $x_b y_b z_b$. The frame $x_I y_I z_I$ is attached to the humerus (or the upper arm of the wing) and is rotating about z_I with the swivel angle θ_I which is the angle between the x_0 axis and the x_I axis in the right-hand sense. The shoulder joint has a radius joint r_0 , and the whole wing has a length a_I from shoulder to the wing tip.

Figure 5.5: The shoulder joint of the rigid wing with one DOF with the coordinate frames drawn in a coincident position, $\theta_1 = 0$.

5.2.1 Direct kinematic of the 1-DOF model

In order to find the transformation from the base frame $x_0y_0z_0$, which is oriented to facilitate the application of the Denavit-Hartenberg notation, to the body coordinate frame $x_by_bz_b$ the body frame is rotated about z_b axis with 90° , then about x_b axis with $\gamma = 58^\circ$, and finally translated with the joint radius r_0 along the axis x_b . The rotation matrices are given by the relations (5.6), the translation matrix is given by (5.7), and then, the homogenous transformation matrix A_0^b representing the location of frame $x_0y_0z_0$ relative to the body frame, $x_by_bz_b$, is obtained using the chaining operation for rotation matrices (5.6) and translation matrix (5.7):

$$R_{z_b} = \begin{bmatrix} \cos 90^\circ & -\sin 90^\circ & 0 & 0 \\ \sin 90^\circ & \cos 90^\circ & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R_{x_b} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \gamma & -\sin \gamma & 0 \\ 0 & \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.6)$$

$$T_{x_b} = \begin{bmatrix} 1 & 0 & 0 & r_0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.7)$$

$$A_0^b = R_{z_b} \cdot R_{x_b} \cdot T_{x_b} = \begin{bmatrix} 0 & -\cos \gamma & \sin \gamma & 0 \\ 1 & 0 & 0 & r_0 \\ 0 & \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.8)$$

The transformation from the humerus frame $x_I y_I z_I$ to the base frame $x_0 y_0 z_0$ is written using the Denavit-Hartenberg notation, where the transformation parameters are:

- The twist angle which is the angle between z_0 and z_I measured about x_0 in the right-hand sense: $\alpha_0 = 0^\circ$.
- The link length: $a_0 = 0$ mm.
- The joint angle which is the angle between x_0 and x_I measured about z_I in the right-hand sense: θ_I .
- The link offset: $d_I = 0$ mm.

Using this parameters and the standard form of the homogenous transformation from relation (5.5), the homogenous transformation matrix A_1^0 from the humerus frame $x_I y_I z_I$ to the base frame $x_0 y_0 z_0$ is:

$$A_1^0 = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.9)$$

The homogenous transformation from the humerus frame $x_I y_I z_I$ to the body frame $x_b y_b z_b$ is computed through the chaining operation:

$$A_1^b = A_0^b \cdot A_1^0 = \begin{bmatrix} -\cos \gamma \cdot \sin \theta_1 & -\cos \gamma \cdot \cos \theta_1 & \sin \gamma & 0 \\ \cos \theta_1 & -\sin \theta_1 & 0 & a_0 \\ \sin \gamma \cdot \sin \theta_1 & \sin \gamma \cdot \cos \theta_1 & \cos \gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.10)$$

Figure 5.6 shows the position vector $\vec{X}_{tip}^{(1)}$ of the wing tip with respect to the humerus frame $x_1 y_1 z_1$. In the matrix form this vector can be written as a column vector:

$$\vec{X}_{tip}^{(1)} = \begin{pmatrix} L_w \\ 0 \\ 0 \\ 1 \end{pmatrix}, \quad (5.11)$$

Figure 5.6: Position vector of the wing tip $\vec{X}_{tip}^{(1)}$ with respect to the humerus frame. L_w is the total length of the wing.

In order to find the position vector of the wing tip with respect to the body attached frame, it can be used the homogenous transformation matrix A_1^b from the humerus frame $x_I y_I z_I$ to the body frame:

$$\vec{X}_{tip}^{(b)} = \begin{bmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \\ 1 \end{bmatrix}_{x_b y_b z_b} = A_1^b \cdot \vec{X}_{tip}^{(l)} = \begin{bmatrix} -L_w \cdot \cos \gamma \cdot \sin \theta_1 \\ L_w \cdot \cos \theta_1 + a_0 \\ L_w \cdot \sin \gamma \cdot \sin \theta_1 \\ 1 \end{bmatrix}, \quad (5.12)$$

The relation (5.12) is the kinematic equation for 1-DOF case and provides the functional relationship between the joint angular displacement θ_1 and the resultant wing tip position. By substituting values of joint displacement in the right-hand side of the kinematic equation, one can immediately find the corresponding wing tip position. The problem of finding the wing tip position for a given set of joint displacements is referred to as the direct kinematics problem.

Regarding the flapping of the *Plecotus auritus* bat, [Norberg76] found that at the start of the downstroke the wings are fully extended with the corresponding positional angle $\varphi_{downstroke} = 153.5^\circ$ of the long wing-axis in the stroke plane, see Figure 5.2 b). The wing then sweeps downwards and forwards fully extended and moves essentially in one plane, tilted 58° to the horizontal. The upstroke starts when the wing has reached the positional angle $\varphi_{upstroke} = 62.8^\circ$, (Figure5.7).

Since, for the case of 1-DOF, the joint angle of the shoulder θ_1 can be written as:

$$\theta_1 = \varphi - 90^\circ$$

with

$$\theta_{1\max} = 63.5^\circ \quad \theta_{1\min} = -27.2^\circ \quad T = 84 \text{ ms}$$

The offset and the amplitude are

$$\theta_{1\text{offset}} = \frac{\theta_{1\max} + \theta_{1\min}}{2} \cong 18^\circ; \quad A = \theta_{1\max} - \theta_{1\text{offset}} = \theta_{1\text{offset}} - \theta_{1\min} = \frac{\theta_{1\max} - \theta_{1\min}}{2} \cong 45.4^\circ$$

Therefore, using a cosine function, the joint angle can be approximated as:

$$\theta_1(t) = \theta_{1_{offset}} + A \cdot \cos\left(\frac{2\pi}{T}t\right)$$

$$\theta_1(t) = 18^\circ + 45.4^\circ \cdot \cos\left(\frac{2\pi}{0.084}t\right), \quad (5.13)$$

Figure 5.7: The variation of the positional angle could be approximated with a harmonic function, (Norberg, 1976).

In the direct kinematic analysis, the joint angles are known and the kinematic equation, (5.12) is solved for the position of some points of interest i.e. wrist, wing tip, tip of 4th finger or tip of 5th finger. For 1-DOF case, the only point of interest is the wing tip. Using MATLAB, the trajectories of the wing tip are plotted in Figure 5.8, for which the coordinates were computed with the relation 5.12. As it was expected the wing tip trajectory is an arc of circle with radius $L_w = 124$ mm in the plane of stroke which is inclined with $\gamma = 58^\circ$ with respect to the horizontal plane.

Figure 5.8: Wing tip trajectory and its projections.

5.2.2 Inverse kinematic of the 1-DOF model

The inverse kinematics problem is assuming that the wing tip position is known and the kinematic equation is solved for the joint angular displacements θ_i which lead to that specified wing tip position. For the 1-DOF case, the kinematic equation (5.12) must be solved for joint displacement θ_I considering the coordinates of the wing tip with respect to the body frame as being known. The relation (5.12) provides three redundant equations to solve for θ_I . Using the third equation and solving for θ_I , it results:

$$\sin \theta_1 = \frac{z_{tip}}{L_w \cdot \sin \gamma}, \quad (5.14)$$

In order for a solution to exist, the right-hand side of (5.14) must have a value between -1 and 1. In the solution algorithm, this constraint would be checked at this time to determine if a

solution exists. Physically, if this constraint is not satisfied, then the wing tip point is too far away for the wing structure to reach it since the chosen length of the wing bones are too short.

As the computed angles can range over a full 360° , it is helpful to make use of the two-argument arctangent MATLAB function, $A\text{tan2}(y, x)$, which computes $\tan^{-1}\left(\frac{y}{x}\right)$, but uses the signs of both x and y to determine the quadrant in which the resulting angle lies. Therefore, the following could be written:

$$\cos \theta_1 = \pm \sqrt{1 - \sin^2 \theta_1}, \quad (5.15)$$

Finally, the angle θ_1 is computed as:

$$\theta_1 = A\text{tan2}(\sin \theta_1, \cos \theta_1), \quad (5.16)$$

Using the MATLAB script for inverse kinematic from Appendix A, the shoulder joint θ_1 is plotted in Figure 5.9. As it can be seen, the inverse kinematic problem produced accurately the joint angle that was used at the direct kinematic.

Figure 5.9: The shoulder angle θ_1 obtained from inverse kinematic of the wing tip.

5.3. Kinematics of 2-DOF model

Using the same DOF in the shoulder joint and the same inclination of the plane of stroke as for the wing with 1-DOF, a second joint is introduced, the elbow joint, with 1-DOF. As in the case of human elbow, the bat elbow is designed for 2-DOF: 1-DOF that produces the forearm flexion and the second one that produces the roll of the wrist resulting in a leading edge flap, (Figure 5.10).

This time the DOF that produces the forearm flexion is introduced as the second DOF for the flexible wing with two DOF. Flexing the forearm is used in order to vary the area of the wing to produce lift during the downstroke and to reduce drag during the upstroke.

Figure 5.10: The roll of the wrist produced by a limited rotation of the forearm and resulting in a leading edge flap to generate thrust during the upstroke (Norberg, 1972).

Figure 5.11 shows the kinematic structure for the flexible wing with two joints – the shoulder joint and the elbow joint – having 2-DOF. The forearm, the hand and the digits together are forming one rigid body with the length a_2 from elbow to the wing tip.

Figure 5.11: The coordinate frames of the 2-DOF wing, drawn in a coincident position, $\theta_1 = \theta_2 = 0$.

5.3.1 Assigning the coordinate frames

The coordinate frames defining the motion in the shoulder joint are similar with the case of 1-DOF wing:

- The fixed body frame $x_b y_b z_b$.
- The fixed shoulder frame $x_0 y_0 z_0$ which is attached to the bat body and shows the inclination of the stroke plane with respect to the horizontal plane.
- The coordinate frame of the humerus $x_1 y_1 z_1$, which is rotating about z_1 with the joint angle θ_1 relative to $x_0 y_0 z_0$.

A new coordinate frame $x_2 y_2 z_2$ is introduced with the elbow joint, which is attached to the wing forearm and is rotating about z_2 with the angle θ_2 relative to the frame $x_1 y_1 z_1$, (Figure 5.11).

5.3.2 Direct kinematic for 2-DOF model

Applying Denavit-Hartenberg notation, the link parameters for coordinate transformations are listed in Table 5.1. The motion of the humerus bone is determined by the same

parameters as for 1-DOF wing. As it can be seen, the only variables are the joint angle displacements θ_1 and θ_2 while the other parameters are constants.

Table 5.1: Link parameters for the 2-DOF flexible wing with revolute joints.

Link (bone)	Coordinate frame	Bone twist angle, α_{i-1}	Common normal, (bone length) a_{i-1}	Joint angle, θ_i	Offset, d_i
Arm	1	0°	0	θ_1	0
Forearm	2	90°	a_1	θ_2	0

The coordinate transformations A_0^b and A_1^0 are similar to the 1-DOF wing, and the transformation from the elbow frame $x_2y_2z_2$ to the shoulder frame $x_1y_1z_1$ is written using the homogenous transformation matrix (5.5) and the forearm parameters listed in Table 5.1:

$$A_2^1 = \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & a_1 \\ 0 & 0 & -1 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.17)$$

As it could be seen, the transformation matrix A_2^1 is only a function of the elbow joint angle θ_2 as the transformation matrix A_1^0 is a function of the shoulder joint angle θ_1 . The transformation matrix A_0^b is a matrix having only constants since it just make the transformation from the shoulder fixed frame $x_0y_0z_0$ to the body fixed frame $x_by_bz_b$, being used to introduce the inclination of the stroke plane. In order to determine the transformation matrix from the elbow frame to the body attached frame, the chaining operation of all the consecutive transformation matrices:

$$A_2^b = A_0^b \cdot A_1^0 \cdot A_2^1 = \begin{bmatrix} s_\gamma s_2 - c_\gamma s_1 c_2 & s_\gamma c_2 + c_\gamma s_1 s_2 & c_\gamma c_1 & -a_1 c_\gamma s_1 \\ c_1 c_2 & -c_1 s_2 & s_1 & a_1 c_1 + a_0 \\ c_\gamma s_2 + s_\gamma s_1 c_2 & c_\gamma c_2 - s_\gamma s_1 s_2 & -s_\gamma c_1 & a_1 s_\gamma s_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.18)$$

where $s_\gamma, c_\gamma, s_1, c_1, s_2, c_2$ is representing $\sin \gamma, \cos \gamma, \sin \theta_1, \cos \theta_1, \sin \theta_2, \cos \theta_2$.

Figure 5.12: The position vectors of the wrist and wingtip with respect to the second frame.

Considering that the axis x_2 is passing through the wrist joint, the position vector of the wrist $\vec{X}_{wrist}^{(2)}$ with respect to the local elbow frame $x_2y_2z_2$ is:

$$\vec{X}_{wrist}^{(2)} = \begin{pmatrix} L_r \\ 0 \\ 0 \\ 1 \end{pmatrix}, \quad (5.19)$$

where $L_r = 40 \text{ mm}$ is the length of the radius bone (Figure 5.12). In order to find the position vector of the wrist with respect to the body attached frame $\vec{X}_{wrist}^{(b)}$, it can be used the homogenous transformation matrix A_2^b from the elbow frame $x_2y_2z_2$ to the body frame:

$$\overrightarrow{X}_{wrist}^{(b)} = \begin{bmatrix} x_{wrist} \\ y_{wrist} \\ z_{wrist} \\ 1 \end{bmatrix}_{x_b, y_b, z_b} = A_2^b \cdot \overrightarrow{X}_{wrist}^{(2)} = \begin{bmatrix} L_r \cdot (s_\gamma s_2 - c_\gamma s_1 c_2) - a_1 c_\gamma s_1 \\ L_r c_1 c_2 + a_1 c_1 + a_0 \\ L_r \cdot (c_\gamma s_2 + s_\gamma s_1 c_2) + a_1 s_\gamma s_1 \\ 1 \end{bmatrix}, \quad (5.20)$$

The relation (5.20) is the kinematic equation for the wrist of the 2-DOF flexible wing and provides the functional relationship between the joint angular displacements θ_1 , θ_2 and the resultant wing tip position. By substituting values of joint displacements in the right-hand side of the kinematic equation, one can immediately find the corresponding wrist position. This kinematic equation for wrist is used further to calibrate the combination of joint angles that are approximating the kinematic of the 2-DOF flexible wing.

5.3.3 Optimization of joint angle displacements

Plecotus auritus bat has an approximate wingspan of 27 cm and 4-DOF up to the wrist whereas, for this case the proposed has wing has just 2-DOF and an inverse kinematic analysis is impossible to find a combination of joint angles θ_1 and θ_2 to mimic the wingtip trajectory. However, the wing with 2-DOF can approximate this trajectory. In order to find the joint angles that approximate this trajectory an optimization of this angle is made using the forward or direct kinematics.

A rough estimate for the range of the swivel angle θ_1 could be done using the front view of the beginning of downstroke and the one of the end of the downstroke. As the Figure 5.13 shows it results a variation between -30° and 40° or 50° . A similar rough estimate for the range of the elbow joint angle θ_2 could be done using the bottom view of the *Plecotus auritus* wingbeat varying between 40° and 100° , considering that the body longitudinal axis of the bat makes an angle of about 20° with the horizontal (Figure 5.14). Considering that the wing flapping is harmonic, as the image processing suggests, the joint angles can be written as:

$$\theta_1 = \theta_{10} + A_1 \cos(\omega t + \varphi_1), \left[^\circ\right]$$

$$\theta_2 = \theta_{20} + A_2 \cos(\omega t + \varphi_2), \left[^\circ\right]$$

Figure 5.13: Rough estimate for the swivel angle θ_1 .

Figure 5.14: Rough estimate for the range of the elbow joint angle θ_2 .

Since the wing is having 2-DOF, the joint angular displacements, an optimization of their combination and of their offset, amplitude and phase is recommendable. Norberg, 1976, provides data for wrist and tip of each digit, but since the kinematic chain for is having less DOF than for wingtip (wrist – 4-DOF, wingtip – 11-DOF) then the wrist is used to find the optimal combination for the joint angles θ_1 and θ_2 . Table 5.2 presents an analysis of the offset θ_{10} and amplitude A_1 influence on the wrist trajectory.

Table 5.2 presents an analysis of the influence of the offset θ_{10} and amplitude A_1 on the wrist trajectory. First, using the range values estimated above an arbitrary definition of these joint angles is considered that is:

$$\theta_1 = 5^\circ + 30^\circ \cos \frac{2\pi}{0.084} t$$

$$\theta_2 = 68^\circ + 30^\circ \cos\left(\frac{2\pi}{0.084}t + 65^\circ\right)$$

where the period of the wingbeat is $T = 0.084$ s.

Then, the offset θ_{10} and the amplitude A_1 of angle are gradually increased, while the joint angle θ_2 remains unchanged. The simulations made with MATLAB, see Appendix B, indicate the trend of wrist trajectory given by the variation of the offset and amplitude. The increase of the offset θ_{10} for the first angle is raising the wrist trajectory along the z_b axis. The increase of the amplitude A_1 is increasing the major axis of the elliptic shape and is tilting it toward the tail of the bat.

Table 5.3 analyzes the influence of the offset θ_{20} and amplitude, A_2 of the second angle θ_2 on the wrist trajectory while the shoulder joint angle θ_1 remains the same as it was chosen. The increase of the offset θ_{20} is decreasing the length of the major axis of the elliptic-like shape for the wrist trajectory. The increase of the amplitude A_2 has a widening effect of the elliptic shape giving it a rounder shape. Table 5.4 represents an analysis of the offset θ_{20} and amplitude, A_2 of the second angle θ_2 on a narrow range. Combining the conclusions learned from the analysis of both tables, an optimization is made and the following angles are proposed to be used further:

$$\theta_1(t) = 5^\circ + 35^\circ \cdot \cos\frac{2\pi}{0.084}t, \quad (5.21)$$

$$\theta_2 = 55^\circ + 30^\circ \cos\left(\frac{2\pi}{0.084}t + 65^\circ\right), \quad (5.22)$$

Table 5.2: Influence of the offset θ_{I0} and amplitude A_I of the shoulder angle θ_I on the wrist trajectory, $L_h = 23$ mm, $L_r = 40$ mm.

Table 5.3: Influence of the offset θ_{20} and amplitude A_2 of the elbow angle θ_2 on the wrist trajectory, $L_h = 23$ mm, $L_r = 40$ mm.

Table 5.4: Influence of the offset θ_{20} and amplitude A_2 of the elbow angle θ_2 on the wrist trajectory, $L_h = 23$ mm, $L_r = 40$ mm – refined.

Figure 5.15 shows a comparison between the wrist trajectory for the natural flyer, *Plecotus auritus* and the one for the optimal joint angle combination that approximate it. In comparison with the trajectory for the natural flyer the approximated trajectory is farther from the origin of the body attached frame which has its origin in the shoulder. This shift is due to the fact that the arm flexion DOF from the shoulder joint is neglected on this first iteration of the wing kinematic. Introducing this DOF in the next iterations of the future work on wing kinematic would give a better approximation.

Figure 5.15: Comparison between (a) the wrist trajectory of the natural flyer, and (b) the approximated solution for the 2-DOF flexible wing.

5.3.4. Inverse kinematic of the 2-DOF model

The inverse kinematics problem is solve the kinematic equation (5.20) for the joint angular displacements θ_1 and θ_2 which lead to a known wrist position with respect to the base frame which for BATMAV is the body attached frame $x_{wrist}^{(b)}$, $y_{wrist}^{(b)}$, $z_{wrist}^{(b)}$. For the 2-DOF flexible wing, the kinematic equation (5.20) must be solved for joint displacement θ_1 and θ_2 considering the coordinates of the wrist with respect to the body frame as being known. The relation (5.20) provides three redundant equations to solve for θ_1 and θ_2 . The equation 5.20 can be written in the matrix form as:

$$\vec{X}_{wrist}^{(b)} = A_2^b \cdot \vec{X}_{wrist}^{(2)} = A_0^b \cdot A_1^0 \cdot A_2^1 \cdot \vec{X}_{wrist}^{(2)}, \quad (5.23)$$

If both sides of the last equation are pre-multiplied first with $(A_0^b)^{-1}$ and then with $(A_1^0)^{-1}$, the kinematic equation for the 2-DOF wing becomes:

$$(A_1^0)^{-1} \cdot (A_0^b)^{-1} \cdot \vec{X}_{wrist}^{(b)} = A_2^1 \cdot \vec{X}_{wrist}^{(2)}, \quad (5.24)$$

Taking the matrix multiplication three redundant equations are obtained, where the unknown angles θ_1 and θ_2 are separated, each one on a different side of the three equations:

$$\begin{bmatrix} -x_{wrist} \cos \gamma \sin \theta_1 + y_{wrist} \cos \theta_1 + z_{wrist} \sin \gamma \sin \theta_1 - a_0 \cos \theta_1 \\ -x_{wrist} \cos \gamma \cos \theta_1 - y_{wrist} \sin \theta_1 + z_{wrist} \sin \gamma \cos \theta_1 + a_0 \sin \theta_1 \\ x_{wrist} \sin \gamma + z_{wrist} \cos \gamma \\ 1 \end{bmatrix} = \begin{bmatrix} a_1 + L_r \cos \theta_2 \\ 0 \\ L_r \sin \theta_2 \\ 1 \end{bmatrix}, \quad (5.25)$$

It is evident that the second equation can be solved for the joint angle θ_1 and that the third one for the joint angle θ_2 . Starting with the joint angle the second equation can be written as:

$$(a_0 - y_{wrist}) \sin \theta_1 = (x_{wrist} \cos \gamma - z_{wrist} \sin \gamma) \cos \theta_1, \quad (5.26)$$

or:

$$\tan \theta_1 = \frac{x_{wrist} \cos \gamma - z_{wrist} \sin \gamma}{a_0 - y_{wrist}}, \quad (5.27)$$

Therefore, using the two-argument arctangent MATLAB function, $A \tan 2(y, x)$, which computes $\tan^{-1}\left(\frac{y}{x}\right)$, but uses the signs of both x and y to determine the quadrant, in which the resulting angle lies, the angle θ_1 is:

$$\theta_1 = A \tan 2(x_{wrist} \cos \gamma - z_{wrist} \sin \gamma, a_0 - y_{wrist}), \quad (5.28.a)$$

or:

$$\theta_1 = A \tan 2(-(x_{wrist} \cos \gamma - z_{wrist} \sin \gamma), -(a_0 - y_{wrist})), \quad (5.28.b)$$

From the third equation of the system (5.25), it results:

$$\sin \theta_2 = \frac{x_{wrist} \sin \gamma + z_{wrist} \cos \gamma}{L_r}, \quad (5.29)$$

Therefore, the following could be written:

$$\cos \theta_2 = \pm \sqrt{1 - \sin^2 \theta_2}, \quad (5.30)$$

And the second angle θ_2 is computed as:

$$\theta_2 = \text{Atan2}(\sin \theta_2, \cos \theta_2), \quad (5.31)$$

Writing a MATLAB script for the inverse kinematics of the 2-DOF flexible wing, see Appendix B, which includes the equations (5.28) and (5.31) the joint angles are computed. Their variation in time is plotted in Figure 5.16. As it can be seen, the analytical calculus for inverse kinematics accurately produces the joint angles that were chosen after their optimization of the direct kinematic.

Figure 5.16: The joint angles θ_1 and θ_2 obtained from inverse kinematic of the wing tip.

5.4. Kinematics of the 3-DOF model

Using the same DOF as in the previous case of 2-DOF flexible, a third joint is introduced, this time the wrist joint. Similar to the human wrist, the bat wrist is a very complex joint having 3-DOF: roll, pitch and yaw (Figure 5.17). Roll is the rotation along the longitudinal axis of the forearm turning the palm to face upward or downward and it helps in generating more thrust. Pitch is the rotation of the hand which helps in flexing the palm to approach the forearm in a downward or upward direction. The wrist pitch helps in folding the wing during upstroke in order to decrease the drag. Yaw is the rotation of the hand which helps in flexing the palm to approach the forearm especially in a backward direction. The wrist yaw helps in folding the wing during roosting time. In order to reduce drag during the upstroke and therefore to increase the wing efficiency, the pitch DOF is introduced for the three DOF flexible wing.

Figure 5.17: The complex joint of wrist. For the first kinematic analysis, only the pitch motion is considered.

5.4.1. Assigning the coordinate frames

The coordinate frames defining the motion in the shoulder and elbow joints are similar with the case of 2-DOF flexible wing:

- The fixed body frame $x_b y_b z_b$.

- The fixed shoulder frame $x_0y_0z_0$ which is attached to the bat body and shows the inclination of the stroke plane with respect to the horizontal plane.
- The coordinate frame of the humerus $x_1y_1z_1$, which is rotating about z_1 with the joint angle θ_1 relative to $x_0y_0z_0$.
- The elbow coordinate frame $x_2y_2z_2$ which is attached to the radius bone and is rotating about z_2 with the angle θ_2 relative to the frame $x_1y_1z_1$

A new coordinate frame $x_3y_3z_3$ is introduced with the wrist joint, which is attached to the wing hand and is rotating about z_3 with the angle θ_3 relative to the elbow frame $x_2y_2z_2$ (Figure 5.18 and 5.19).

Figure 5.18: The coordinate frames assigned for the 3DOF flexible wing. The coordinate frames are drawn in a coincident position, $\theta_1 = \theta_2 = \theta_3 = 0$.

Figure 5.19: Bat wing with the assigned coordinate frames.

5.4.2. Direct kinematics for the 3-DOF model

Applying Denavit-Hartenberg notation, the link parameters for coordinate transformations are listed in Table 5.5, where $a_1 = 29$ mm is the length of the humerus bone, and $a_2 = L_r = 40$ mm is the length of the radius bone – the forearm. The motion of the humerus bone is determined by the same parameters as for 1-DOF wing. As it can be seen, the only variables are the joint angle displacements θ_1 , θ_2 and θ_3 while the other parameters are constants.

Table 5.5: Link parameters for the 3-DOF flexible wing with revolute joints.

Link (bone)	Coordinate frame	Bone twist angle, α_{i-1}	Common normal, (bone length) a_{i-1}	Joint angle, θ_i	Offset, d_i
Arm	1	0°	0	θ_1	0
Forearm	2	90°	a_1	θ_2	0
Hand	3	-90°	a_2	θ_3	0

The coordinate transformations A_0^b , A_1^0 and A_2^1 are similar to the 2-DOF wing. Subsequently, the homogenous transformation matrix from frame $x_3y_3z_3$ to frame $x_2y_2z_2$ is established using the Denavit-Hartenberg notation with the parameters from Table 5.5:

$$A_3^2 = \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 & 0 & a_2 \\ 0 & 0 & 1 & 0 \\ -\sin \theta_3 & -\cos \theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.32)$$

Therefore, transformation matrix A_3^b from the wrist coordinate frame $x_3y_3z_3$ to the body frame $x_by_bz_b$ can be written using the chaining operation as:

$$A_3^b = A_0^b \cdot A_1^0 \cdot A_2^1 \cdot A_3^2, \quad (5.33)$$

After the matrix multiplication it results the matrix A_3^b , relation (5.35), with intricate terms. The first part of 3×3 matrix represents the orientation of the wrist frame $x_3y_3z_3$ with respect to the body frame $x_by_bz_b$ and the last column of matrix represents the position of the wrist frame $x_3y_3z_3$ with respect to the body frame. From this last column results the coordinates of the wrist relative to the body frame:

$$\begin{aligned} x_{wrist} &= (s_\gamma s_2 - c_\gamma s_1 c_2) a_2 - c_\gamma s_1 a_1 \\ y_{wrist} &= c_1 c_2 a_2 + c_1 a_1 + a_0, \\ z_{wrist} &= (c_\gamma s_2 + s_\gamma s_1 c_2) a_2 + s_\gamma s_1 a_1 \end{aligned} \quad (5.34)$$

$$A_3^b = \begin{bmatrix} c_3(s_\gamma s_2 - c_\gamma s_1 c_2) - c_\gamma c_1 s_3 & s_3(c_\gamma s_1 c_2 - s_\gamma s_2) - c_\gamma c_1 c_3 & s_\gamma c_2 + c_\gamma s_1 s_2 & (s_\gamma s_2 - c_\gamma s_1 c_2) a_2 - c_\gamma s_1 a_1 \\ -s_1 s_3 + c_1 c_2 c_3 & -s_1 c_3 - c_1 c_2 s_3 & -c_1 s_2 & c_1 c_2 a_2 + c_1 a_1 + a_0 \\ c_3(s_\gamma s_1 c_2 + c_\gamma s_2) + s_\gamma c_1 s_3 & -s_3(s_\gamma s_1 c_2 + c_\gamma s_2) + s_\gamma c_1 c_3 & c_\gamma c_2 - s_\gamma s_1 s_2 & (c_\gamma s_2 + s_\gamma s_1 c_2) a_2 + s_\gamma s_1 a_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5.35)$$

where, for simplification it is noted $s_1, c_1, s_2, c_2, s_3, c_3, s_\gamma, c_\gamma$ as $\sin \theta_1, \cos \theta_1$, etc.

In order to find the wingtip coordinates with respect to the body frame, the wingtip coordinates relative to the local wrist frame $x_3y_3z_3$ are transformed to the body frame using

the homogenous transformation A_3^b from the wrist frame to the body frame. The position vector of the wing tip $\vec{X}_{tip}^{(3)}$, Figure 5.19, with respect to the local wrist frame $x_3y_3z_3$ is:

$$\vec{X}_{tip}^{(3)} = \begin{pmatrix} x_{3tip} \\ 0 \\ z_{3tip} \\ 1 \end{pmatrix}, \quad (5.36)$$

Considering that the palm and digit section of the wing has a rigid structure, it is assumed that the wingtip is in plane $O_3x_3z_3$. Therefore, the wingtip position vector with respect to the body frame is:

$$\vec{X}_{tip}^{(b)} = \begin{bmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \\ 1 \end{bmatrix}_{x_b, y_b, z_b} = A_3^b \cdot \vec{X}_{tip}^{(3)}$$

or

$$\vec{X}_{tip}^{(b)} = \begin{bmatrix} \left((s_y s_2 - c_y s_1 c_2) c_3 - c_y c_1 s_3 \right) x_{3tip} + \left(c_y s_1 s_2 + s_y c_2 \right) z_{3tip} + \left(s_y s_2 - c_y s_1 c_2 \right) a_2 - c_y s_1 a_1 \\ \left(c_1 c_2 c_3 - s_1 s_3 \right) x_{3tip} - c_1 s_2 z_{3tip} + c_1 c_2 a_2 + c_1 a_1 + a_0 \\ \left((c_y s_2 + s_y s_1 c_2) c_3 + s_y c_1 s_3 \right) x_{3tip} + \left(c_y c_2 - s_y s_1 s_2 \right) z_{3tip} + \left(c_y s_2 + s_y s_1 c_2 \right) a_2 + s_y s_1 a_1 \\ 1 \end{bmatrix}, \quad (5.37)$$

Using the same formulation for the shoulder joint angle θ_1 and the elbow joint angle θ_2 that was derived as a calibration on the wrist trajectory, the wingtip coordinates could be computed as a function of these angles and of the wrist angle θ_3 .

5.4.3. Joint angle optimization for wrist trajectory

Using the equations (5.37) to find the wingtip coordinates with respect to the body frame the optimization of the joint angles is made using MATLAB, see APPENDIX C, in a similar way as for optimization for the 2-DOF wing. Since the angles θ_1 and θ_2 were calibrated using

the wrist trajectory for the 2-DOF case and since the third DOF was introduced after the wrist joint meaning that it does not affect its position their formulation will be the same. With respect to the wrist angle it can be said that it will have negative values with respect to the configuration of the coordinate frames $x_2y_2z_2$ and $x_3y_3z_3$. Roughly its range is between -60° or -70° during the upstroke when the wing is folded and 0° for the downstroke when the wing is fully stretched. This estimate is shown in the plot from Figure 5.20.

Figure 5.20: Rough estimate of the range of the angle given by inspection of the wingbeat picture.

Table 5.6: Influence of the offset θ_{30} and amplitude A_3 of the wrist angle θ_3 on the wingtip trajectory, $L_h = 23$ mm, $L_r = 40$ mm, $L_d = 75$ mm
 $\theta_1 = 5^\circ + 35^\circ \cos \omega t$; $\theta_2 = 55^\circ + 30^\circ \cos(\omega t + 65^\circ)$.

Table 5.7: Influence of the offset θ_{30} and amplitude A_3 of the wrist angle θ_3 on the wingtip trajectory, $L_h = 23$ mm, $L_r = 40$ mm, $L_d = 75$ mm.
 $\theta_1 = 5^\circ + 35^\circ \cos \omega t$; $\theta_2 = 55^\circ + 30^\circ \cos(\omega t + 65^\circ)$.

Table 5.8: Influence of the offset θ_{30} and amplitude A_3 of the wrist angle θ_3 on the wingtip trajectory, $L_h = 23$ mm, $L_r = 40$ mm, $L_d = 55$ mm.
 $\theta_1 = 5^\circ + 35^\circ \cos \omega t$; $\theta_2 = 55^\circ + 30^\circ \cos(\omega t + 65^\circ)$.

Table 5.9: Influence of the offset θ_{30} and amplitude A_3 of the wrist angle θ_3 on the wingtip trajectory, $L_h = 23$ mm, $L_r = 40$ mm, $L_d = 55$ mm.
 $\theta_1 = 5^\circ + 35^\circ \cos \omega t$; $\theta_2 = 55^\circ + 30^\circ \cos(\omega t + 65^\circ)$.

For Tables 5.6 to 5.9, in order to improve the trajectory of the wingtip, the offset θ_{30} , the amplitude A_3 and the phase φ_3 are varied, while the joint angles θ_1 and θ_2 are constant as they were optimized previously. An optimal solution is chosen for the wrist angle θ_3 :

$$\theta_2 = -10^\circ + 40^\circ \cos\left(\frac{2\pi}{0.084}t - 80^\circ\right)$$

Figure 5.21: Comparison between (a) the wingtip trajectory of *Plecotus auritus*, and (b) the approximated solution for the 3-DOF flexible wing.

5.4.4. Wing tip inverse kinematic

Using the joint angles, θ_1 and θ_2 derived with the relations (5.28) and (5.29) in the inverse kinematic of the wrist, we move on toward to wing tip in order to derive the pitch angle of the wrist, θ_3 , from the coordinates of the wing tip, x_{3d} , y_{3d} , z_{3d} , with respect to the body frame. For the 3-DOF wing, the inverse kinematics problem is solve the kinematic equation (5.37) for the wrist joint angular displacements θ_3 assuming that the coordinates of the wingtip with respect to the body frame are known. If both sides of the kinematic equation (5.37) are pre-multiplied first with $(A_0^b)^{-1}$ and then with $(A_1^0)^{-1}$, and finally with $(A_2^1)^{-1}$ the kinematic equation for the 3-DOF wing becomes:

$$\left(A_2^1\right)^{-1} \cdot \left(A_1^0\right)^{-1} \cdot \left(A_0^b\right)^{-1} \cdot \overrightarrow{X}_{tip}^{(b)} = A_3^2 \cdot \overrightarrow{X}_{tip}^{(3)}, \quad (5.38)$$

where

- $X_{3digit}^{(b)} = [x_{3d} \ y_{3d} \ z_{3d} \ 1]^T$ - is the position vector of the third digit tip with respect to the body frame;
- $X_{3digit}^{(3)} = [x_{3tip} \ 0 \ z_{3tip} \ 1]^T$ - is the position vector of the third digit tip with respect to the local coordinate, $x_3y_3z_3$, attached to the hand-digit assembly (Figure 5.19).

Taking the matrix multiplication the following equations are obtained, where the known angles θ_1 and θ_2 are on the left side and the unknown wrist angle is on the right side:

$$\begin{aligned} (s_\gamma s_2 - c_\gamma s_1 c_2) x_d + c_1 c_2 y_d + (c_\gamma s_2 + s_\gamma s_1 c_2) z_d - a_0 c_1 c_2 - a_1 c_2 &= c_3 x_{3tip} + a_2 \\ (s_\gamma c_2 + c_\gamma s_1 s_2) x_d - c_1 s_2 y_d + (c_\gamma c_2 - s_\gamma s_1 s_2) z_d + a_0 c_1 s_2 + a_1 s_2 &= z_{3tip} \\ c_\gamma c_1 x_d + s_1 y_d - s_\gamma c_1 z_d - a_0 s_1 &= -s_3 x_{3tip} \end{aligned} \quad (5.39)$$

The third trigonometric equation of this system can be written in the form:

$$\sin \theta_3 = \frac{a_0 s_1 + s_\gamma c_1 z_d - c_\gamma c_1 x_d - s_1 y_d}{x_{3tip}}, \quad (5.40)$$

and

$$\cos \theta_3 = \pm \sqrt{1 - \sin^2 \theta_3}$$

Therefore, using the two-argument arctangent MATLAB function, $A_{tan2}(y, x)$, which computes $\tan^{-1}\left(\frac{y}{x}\right)$, but uses the signs of both x and y to determine the quadrant, in which the resulting angle lies, the angle θ_3 is

$$\theta_3 = A_{tan2}(\sin \theta_3, \cos \theta_3). \quad (5.41)$$

Using the relations (5.28), (5.29) and (5.41) we solve for the inverse kinematic of the wingtip for the 3-DOF wing.

Figure 5.22: The joint angles for the 3-DOF wing.

5.5. Conclusions

In this chapter, the kinematic of the simplified model was analyzed starting from the simplest model with 1-DOF and gradually the flexibility of the wing was increased up to 3-DOF model. In order to make the transformations from the local coordinate frames to the body attached frame the Denavit-Hartenberg notation was employed, making possible to organize the analytical model of the wing kinematic.

For 2-DOF the wrist trajectory was used to calibrate the shoulder and elbow joint angles which were used to find a solution for the wrist angle to approximate the wingtip trajectory for the 3-DOF wing. Figure 5.23 shows a comparison between the wingtip trajectory of the

natural flyer, *Plecotus auritus* and the 3DOF kinematic model, as well as their projections on lateral, frontal and top planes where the axes have equal scale for their coordinates:

- the lateral view in plane $x_b z_b$;
- the frontal view in plane $y_b z_b$;
- the top view in plane $x_b y_b$;

Figure 5.23: Comparison of the wingtip trajectory between the *Plecotus auritus* and the kinematic model.

The wrist of the natural flyer is having 2DOF during the wingstroke, Figure 5.24:

- the pitch motion of the wrist in order to vary the wing area;
- the roll motion of the wrist which gives a propeller-like shape to the wing and enables the finger portion of the wing to generate thrust during the downstroke;

Figure 5.24 presents a comparison between the trajectory of the wingtip for *Plecotus auritus* and for the 3DOF Model in the bottom view. *Plecotus auritus* combines both wrist pitch and

wrist roll motions during the wingstroke. For the downstroke the hand wing is gradually rotated with the palm downward to generate thrust, and at the end of upstroke during the flick phase, the hand wing is suddenly jerked with the palm upward and frontward, Figure 5.25.

Figure 5.24: The effect of the wrist DOF on the wingtip trajectory.

Figure 5.25: Lateral view of the wingtip trajectory.

The wrist roll during the flick phase is shifting the wingtip trajectory toward back of the bat. It thus appears as if the next step of refinement should be the inclusion of the wrist roll as a fourth degree of freedom. This effect will not only be useful for a better description of the wingtip trajectory but also introduces an important mechanism known to contribute to thrust generation.

CHAPTER 6

CONCLUDING REMARKS AND FUTURE WORK

The main objective of this project is to develop a biologically inspired bat-like MAV with flexible and foldable wings for flapping flight and the particular objective of this work was to analyze the kinematics of the flapping flight in order to prepare for the future phase of the project: smart material actuation using SMA wires.

In Chapter 2 an extended analysis of the morphological parameters and the flight parameters was done starting with small birds and bats flight and going down to insect flight. The results of this analysis showed that bats are well suited for the mission expected from a MAV since they can operate effectively at a greater range of speeds, due to their camber variation and employ a very maneuverable flight, helping to avoid obstacles while flying in small spaces (i.e. search and rescue missions). This analysis showed that a bat-like wing can be easily actuated and controlled during flight using SMA wires, compared to birds or insect wing.

A better understanding of future ‘mechanical muscle’ implementations on a bat-like platform was the results of the analysis on the bat muscle actuation system which was done in Chapter 3. Due to their complexity, from the engineering point of view, only a limited number of muscles were selected to actuate the flexible wing. A computer model of a MAV platform incorporating SMA wires, wings and platform body, was created assisted by SolidWorks software.

Chapter 5 presents thorough kinematic analysis of the flapping motion generated by the simplified engineering system with an increasing number of degrees of freedom. The models employ the standard Denavit-Hartenberg formalism, commonly employed for the description of robotic systems, and present a systematic study of the effect of joint angle motion parameters on the resulting trajectories at the bat’s wrist or wingtip. The results are compared to experimental data available in the biological literature and potential improvements are discussed.

In the future, the optimization of a 4-DOF wing structure will be performed using the least square method for which the kinematic analysis from the Chapter 5 provided a suitable initial guess in order to find the optimal solution that approximates the 11-DOF wing structure of the natural flyer as closest as possible.

In order to investigate the extent of SMA actuation capability for a wing of reduced size, a computer assisted tensile test setup was designed to study the mechanical properties of SMA micro-scale wires. The results of the investigation coupled with the choice of a suitable 4-DOF kinematic structure will be used to optimize the length and the attachment location of the wires such that enough lift, thrust and wing stroke will be obtained.

Another significant future step will be the kinematic modeling of differential motion and the aerodynamic analysis completed with a laboratory experimentation of the resulted lift and thrust of the flapping platform.

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APPENDICES

APPENDIX 1

MATLAB SCRIPT FOR 1-DOF MODEL

Plot of the wing tip trajectory for 1-DOF model:

```
% MATLAB script for DIRECT KINEMATIC of 1 DOF Wing
clear all
clc
clf
a0 = 1.5;% Radius of the shoulder joint [mm]
Lw = 124;% Wing Length [mm]
gm = 58*pi/180;% The angle of the plane stroke

for t = 0:0.001:0.084
    th1 = (18+45.4*cos(2*pi/0.084*t))*pi/180;
    xtip = -Lw*cos(gm)*sin(th1);
    ytip = Lw*cos(th1)+a0;
    ztip = Lw*sin(gm)*sin(th1);
    plot3(xtip,ypoint,ztip,'.r','markersize',20)
    hold on
    plot3(-60,ypoint,ztip,'ob','markerfacecolor','b','markersize',2)
    hold on
    plot3(xtip,30,ztip,'*m','markersize',5)
    hold on
    plot3(xtip,ypoint,-50,'dk','markerfacecolor','k','markersize',5)
end
title('\bf{Wing tip trajectory for \theta_1 = 18^\circ+45.4^\circ\cos\omega t}',...
      'FontSize',12)
xlabel('\bf{x_b [mm]}','FontSize',12)
ylabel('\bf{y_b [mm]}','FontSize',12)
zlabel('\bf{z_b [mm]}','FontSize',12)
axis normal;
set(gca,'LineWidth',2,'FontSize',10)
grid on

view([135 20])
legend('wing tip trajectory','frontal view','lateral view','top view',3);
% d = [t' xtip' ytip' ztip'];
% xlswrite('wingtip_coordinates.xls',d)
```

APPENDIX 2

MATLAB SCRIPT FOR 2-DOF MODEL

Plot of the wrist trajectory for the 2-DOF model with the suitable combination of the joint angles θ_1 and θ_2 :

```
% MATLAB script for DIRECT KINEMATICS of the FLEXIBLE WING with 2DOF
clear all
clc
clf
a0 = 1.5; % Shoulder joint radius, [mm]
a1 = 21.5; % Humerus length, [mm]29
Lr = 40;% Length of the forearm, [mm]40
gm = 58*pi/180; % the inclination angle of the stroke plane
% 1.745 rad = 100 deg; 1.396rad = 80deg;
for t = 0:0.001:0.084
    th1 = (5+35*cos(2*pi/0.084*t-0*pi/180))*pi/180;
    th2 = (55+30*cos(2*pi/0.084*t+65*pi/180))*pi/180;

    xw = (-cos(gm)*sin(th1)*cos(th2)+sin(gm)*sin(th2))*Lr-
cos(gm)*sin(th1)*a1;
    yw = cos(th1)*cos(th2)*Lr+cos(th1)*a1+a0;
    zw =
(sin(gm)*sin(th1)*cos(th2)+cos(gm)*sin(th2))*Lr+sin(gm)*sin(th1)*a1;

    plot3(xw,yw,zw,'.r','markersize',20)
    hold on
    plot3(0,yw,zw,'ob','markerfacecolor','b','markersize',2)
    hold on
    plot3(xw,10,zw,'*m','markersize',5)
    hold on
    plot3(xw,yw,-20,'dk','markerfacecolor','k','markersize',5)
end
% title('\theta_1 = 18^o+45.4^ocos\omega t; \theta_2 =
35^o+25^ocos(\omega t+80^o)',...
% 'FontSize',18)
title('\theta_1=10+30cos\omegat \theta_2=68+30cos(\omegat+65),
[^o]','FontSize',18)
% title('L_h = 24 L_r = 40, [mm]','FontSize',18)
xlabel('\bf{x_b, [mm]}','FontSize',18)
ylabel('\bf{y_b, [mm]}','FontSize',18)
zlabel('\bf{z_b, [mm]}','FontSize',18)
set(gca,'LineWidth',2,'FontSize',18)
set(gca,'YTick',[10;20;30;40;50;60;70])
set(gca,'XTick',[0;10;20;30;40])
set(gca,'ZTick],[-20;-10;0;10;20;30;40;50])
axis([0 40 10 70 -20 50]);
grid on
view([138 12])
```

APPENDIX 3

MATLAB SCRIPT FOR 3-DOF MODEL

Animation for the wingtip trajectory of the 3-DOF model:

```
clear all
clc
clf
a0 = 1.5; % Shoulder joint radius, [mm]
a1 = 21.5;%29; % Humerus length, [mm]
a2 = 40;% radius length, [mm]
Ld = 55;% Length of the 3rd digit [mm]
xtip3 = Ld*cos(31.68*pi/180); % x coord of the wingtip relative to x3y3z3
frame, [mm]
ztip3 = -Ld*sin(31.68*pi/180); % z coord of the wingtip relative to x3y3z3
frame, [mm]
gm = 58*pi/180; % the inclination angle of the stroke plane
figure(1)
fig = figure(1);
set(fig, 'DoubleBuffer', 'on');
set(gca, 'xlim',[0 1], 'ylim',[60 160], 'nextplot', 'replace', 'Visible', 'on');
hold on
fps = 4;
aviobj = avifile('Wing_tip_ANIMATION.avi', 'fps', fps, 'quality', 100);

for i = 1:84
    t = 0.001*(i);
    th1 = (5+35*cos(2*pi/0.084*t-0*pi/180))*pi/180;
    th2 = (55+30*cos(2*pi/0.084*t+65*pi/180))*pi/180;
    th3 = (-10+40*cos(2*pi/0.084*t-80*pi/180))*pi/180;

    xtip = ((-cos(gm)*sin(th1)*cos(th2)+sin(gm)*sin(th2))*cos(th3)-
cos(gm)...
        *cos(th1)*sin(th3))*xtip3+(cos(gm)*sin(th1)*sin(th2)+sin(gm)*...
        cos(th2))*ztip3+(-cos(gm)*sin(th1)*cos(th2)+sin(gm)*sin(th2))*...
        a2-cos(gm)*sin(th1)*a1;
    ytip = (cos(th1)*cos(th2)*cos(th3)-sin(th1)*sin(th3))*xtip3-
cos(th1)*...
        sin(th2)*ztip3+cos(th1)*cos(th2)*a2+cos(th1)*a1+a0;
    ztip =
((sin(gm)*sin(th1)*cos(th2)+cos(gm)*sin(th2))*cos(th3)+sin(gm)*...
        cos(th1)*sin(th3))*xtip3+(-sin(gm)*sin(th1)*sin(th2)+cos(gm)*...
cos(th2))*ztip3+(sin(gm)*sin(th1)*cos(th2)+cos(gm)*sin(th2))*a2+...
        sin(gm)*sin(th1)*a1;
    plot3(xtip,ytip,ztip, 'r', 'markersize', 20)
    hold on
    plot3(-40,ytip,ztip, 'ob', 'markerfacecolor', 'b', 'markersize', 2)
    hold on
    plot3(xtip,60,ztip, 'm', 'markersize', 5)
    hold on
```



```

plot3(xtip,ytip,-40,'dk','markerfacecolor','k','markersize',5)

set(gca,'DrawMode','fast')
frame = getframe(fig);

title('\bf{Wingtip trajectory - model}','FontSize',18)
xlabel('\bf{x_b, [mm]}','FontSize',18)
ylabel('\bf{y_b, [mm]}','FontSize',18)
zlabel('\bf{z_b, [mm]}','FontSize',18)
set(gca,'LineWidth',2,'FontSize',18)
axis([-40 80 60 140 -40 100]);
set(gca,'ZTick',[-40;-20;0;20;40;60;80;100])
grid on
view([138 12])
aviobj = addframe(aviobj,frame);
end

aviobj = close(aviobj);
disp('Movie Finished');

```