BEYOND BIOLOGICALLY-INSPIRED INSECT FLIGHT

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ABSTRACT

Important philosophical differences exist between "Biomimetic" air vehicle designs and "Biologically-Inspired" air vehicle designs. This paper describes these differences with application to micro air vehicle designs. The initial biological inspiration may not always be sufficient to lead to a viable and implementable design, so techniques not found in creation may need to be employed. Just as the wheel is not a biological development, but results in optimal solution to various locomotive problems, so too are there aerodynamic methods which leverage biology, but go beyond biological schemes to produce higher performance, manufacturable solutions to flight at small scales. The fundamentals of flight at these scales is discussed and an example is given of a biologically inspired system that extends the design beyond biomimicry.

1.0 BIOLOGICAL INSPIRATION

Many researchers have turned to birds and insects as models in an attempt to leverage what already works at small flight scales. In most cases however, a biomimetic approach has been taken wherein an avian or insect analog is copied. Since everything in creation capable of powered flight uses flapping wings, researchers have endeavored to make flapping wing machines.

Almost universally, these flapping machines restrict their motion to kinematically-correct, symmetric flapping that is often mechanically coupled, allowing only hovering or steady forward flight. [1] These designs do not replicate the mechanisms used by the insects and birds to modulate the flight envelope in speed, direction, and orientation. Study of the unsteady aerodynamics of the flapping wing at a design point is the justification for creating these mechanical testbeds, but often free flying systems are extrapolated from these experiments with little regard for the complexity of miniaturization, full control, and self-powered free flight in a machine that are manufacturable.

It is therefore critically important to make a distinction between *biological mimicry* (biomimetics) and *biological inspiration*. A completely biomimetic wing flapping solution is difficult to design with current technology and may be even more difficult to implement. On the other hand, biological inspiration may lead to a better solution for a given design space than that afforded by the biological entity itself. Therefore biological models serve as a good starting point, but the design must not be constrained by the limitations of the model– in fact, going beyond the biological model could provide an even better solution than the original source of inspiration.

One might ask, in traveling along a prepared road surface from point A to point B in the minimum amount of time while expending minimum energy, is it better to hop, slide (like a snail), slither, or crawl? In each case, a biological analog can be copied, but the optimal solution actually falls outside the realm of biology. The wheel, as a biological structure, does not occur in nature, but wheels pro-

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vide a better solution than any of the biomimetic approaches when considered in the context of the aforementioned locomotion problem.

Ten principals that should be considered when designing a robotic flight vehicle based on aspects of a biological system are as follows (adapted from [2]):

1. *Biomimetics is a good starting point.* There is a wealth of untapped knowledge contained in the realm of nature. In most cases biological systems outperform anything devised by mankind when considering applications that are not on the fringe of performance (extreme temperatures, speeds, etc.), It is therefore reasonable to gain an understanding of how biological systems cope with situations that are also of interest to design of aerial robots.

2. *Strict adherence to biomimetic "guidance" can result in non-optimal performance solutions or unmanufacturable systems.* Merely copying biological morphology, kinematics, or behavior may not lead to an optimal robotic solution simply because it is derived from a biological entity, but should such a solution be achieved, it may be unimplementable due to external constraints. These constraints could include the inability to reproduce analogs for biological structures due to lack of suitable materials or nonexistent manufacturing processes.

3. *Thinking outside the box is always desirable, but sometimes optimal solutions fall within "the box".* The obvious is not always apparent to those who are seeking innovative solutions. The allure of biological inspiration may temp the designer to first consider a how natural systems implement certain behaviors without considering well established techniques. Everything in creation that flies, does so with flapping wings; but there is little warrant to begin a new passenger aircraft design by considering hummingbird wing mechanics.

4. *Biomimetic point solutions may not be practical apart from the "system".* Components of biological systems typically work in concert with one another synergistically to achieve extraordinary behaviors. Copying a single facet of a biological system may not achieve the desired result in the absence of its supporting elements. The flight control and sensory systems of a bird allow it to transition from forward flight to a precision perch on small surfaces (e.g., the top of a flag pole). To merely implement a flapping wing does not impart the ability required by an aerial robot to perch like a bird.

5. *Simply being able to beat wings isn't enough— one must be able to develop the power necessary to fly.* Many flapping wing machines have been devised which aptly demonstrate the correct kinematics for flight, but few can support their own weight in flight, much less that of their power source. Apart from the fabled flights of Icharus, attempts such as DaVinci's human-powered flapping wing machine have been tried with no success over the ages. Synthetic muscle technologies such as piezoelectric elements, shape-memory alloys, rheological fluids, and electro-polymers offer an array of electrically-controlled actuators which have been touted as a potential source of power for biologically-inspired robots, but all have yet to demonstrate sufficient efficiency to lift even the best high energy density battery. Piezoelectrically-actuated flapping wings have been demonstrated to flap for hours from a single watch battery, but at no time was the battery in danger of being lofted into flight. [3]

6. *Biomimetic flapping is structurally complex, leading to difficulties in flight control, manufacturing, and weight*. The muscle structure of an insect wing is very complicated with opposing muscles at divergent angles. In addition, the wing is intimate to the exoskeleton such that deformation of these structures results in wing motion and energy recovery in a resilient material called resilin. Bird wings have muscles at not only the base, but out the wing itself in order to control airfoil shape by deflecting feathers for nuances of control during maneuvers. Replication of these actuator systems in an aerial robot is not trivial. As the size of the aerial robot decreases, the difficulty in building and attaching actuators is compounded.

7. *Means to control stability and to navigate are non trivial*. Most demonstrations of wing flapping are typically less than truly biomimetic because although they may create lift, drag, and thrust, rarely has the ability to do this in an controlled asymmetric manner been incorporated in the design. The main reason is complexity and added weight. Control moments can be created in a flapping wing system by various means including changes in flap angle, span, rate, or wing angle of attack. Birds tend to use all of these flight modulation techniques whereas insects tend to rely mainly on asymmetric changes in angle of attack from one side to the other. Mechanical implementations of these independently-controllable degrees of freedom are problematic at small scales, and heavy at larger ones. Is it any wonder that most free-flying flapping wing machines (e.g., ornithopters after DeLaurier; see Figure 1) end up being a synthesis of birds and airplanes? The flapping bird wings provide lift and thrust while an airplane tail (rudder/elevator) provides the moments necessary for controlled flight.

Figure 1. A DeLaurier 2002 flapping wing machine: a synthesis of birds and airplanes.

8. *Poor integration of all flight systems leads to unmanageable weight*. "Micro" air vehicles, the smallest aerial robots to have received serious attention, differ from larger aerial robots in not only their low Reynolds number surfaces, but also in design philosophy. Unlike larger UAVs which can be multipurpose "trucks" containing black-box subsystems, MAVs must have tightly integrated multipurpose systems in order to manage weight. Structures such as wings need to double as antennas, batteries can become aerodynamically conformal– even becoming part of the air vehicle structure itself. Just as a mammal's bones provide structure, hinge points, attachments for musculature, and serve as red blood cell factories, so the components of a tiny air vehicle must exhibit multiple functions for the sake of efficiency. Aerovironment has demonstrated a battery that serves as part of the wing structure in order to reduce weight and increase endurance in their WASP MAV (see Figure 2). [4] The biologically-inspired Entomopter is one of the most integrated MAV designs with a chemical propulsion system that not only creates thrust and lift, but also enables flight control, joint lubrication, obstacle avoidance, altimetry, and electrical power generation. [5]

Figure 2. AeroVironment "Wasp" MAV.

9. *Designs which do not capitalize on resonance waste energy*. All creatures capable of sustained powered flight do so with resonant systems. Flight is expensive from an energy standpoint. Brute force biological wing flapping can result in flight, but at a great cost in fuel.

Fuel is heavy, so a practical limit on the fuel that can be carried also places a limit on endurance. The act of flapping a wing involves accelerating a mass in one direction and then decelerating the same mass in preparation for a reversal in direction. Brute force flapping burns energy to achieve this reversal. Biological systems store kinetic wing energy within their structures as potential energy to be released upon wing reversal. This is the basis for a resonant system that requires only periodic (at the resonant frequency) energy input rather than a continuous brute force energy expenditure to accelerate wing mass only to fight its inertia moments later.

10. *The average power density for present battery technology is marginal for small scale flapping wing flight*. Small birds and insects are consumed with the task of energy harvesting: the search for food. Hummingbirds, the smallest of all avians, feeding on dilute nectar can ingest nearly three times their body mass in nectar per day to sustain life and mobility. [6, 7] Their small bodies can not carry large amounts of food, so to improve efficiency they choose high energy foods that provide immediate energy access (sugars) as do many insects. Tiny aerial robots suffer from the same need for readily available energy. The energy density of the best battery technologies currently available still cannot match that which is locked chemically in various compounds such as sugars. For example, more energy can currently be extracted from a drop of gasoline than a battery the size of a drop of gasoline. Some have advocated energy harvesting through the use of solar panels on MAVs. Unfortunately the efficiency of current solar cells (roughly 5% for common cells, ranging up to 28% for some of the best triple-junction gallium arsenide space-qualified cells) in sizes that could be carried by a MAV is insufficient for sustained flight. [8] The extra weight of such cells negates their use as an endurance extender and their low voltage output is incompatible with many of the electronic actuators proposed (e.g., piezoelectric, electro polymers, etc.). Finally, night operation or flight through shadows is precluded.

2.0 NATURAL SYSTEMS IN FLIGHT

How do small biological entities cope with flight and how is it different at small scales? Clearly nothing is able to sustain flight in the whole of creation apart from flapping wings. Less discussed is the issue of scale. No biological entity over a certain size possesses the ability to sustain flight. The largest creatures capable of flight are the albatross and condor which are generally soaring gliders weighing around 13 kg (30 lbs). All other species larger than this are flightless (the issue of the extinct pterosaurs and their flight viability under present Earth conditions is a subject of debate– this discussion will focus only on extant observable species). The soaring birds are not particularly powerful. Perhaps the most powerful bird is the Berkut Eagle which has been bred specifically for size and ferocity for many centuries by the turko-mongol people as an imperial hunting bird. These birds have been bread for strength and size since the time of Ghengis Khan and there has been no record of a Berkut Eagle exceeding 11 kg (25 lb). [9] Muscle fiber contraction force limits the size of the flapping winged creature. This is because muscle tissue mass scales as a function of cross section in mammalian creatures, and not species. Increasing the muscle force required to lift the creature requires increased muscle mass and beyond a certain point the forces evolved in the muscle tissue are incapable of lifting the weight of the muscle by aerodynamic means achievable in a flapping wing.

“It appears that the maximum force or stress that can be exerted by any muscle is inherent in the structure of the muscle filaments. The maximum force is roughly 3 to 4 $\mathrm{kgf/cm^2}$ cross section of muscle (300 - 400 $\mathrm{kN/m^2}$). This force is body-size independent and is the same for mouse and elephant muscle. The reason for this uniformity is that the dimensions of the thick and thin muscle filaments, and also the number of cross-bridges between them are the same. In fact the structure of mouse muscle and elephant muscle is so similar that a microscopist would have difficulty identifying them except for a larger number of mitrochondria in the smaller animal. This uniformity in maximum force holds not only for higher vertebrates, but for many other organisms, including at least some, but not all invertebrates.” [10]

At the other end of the size scale, powered flight still involves flapping wings, but the unsteady aerodynamics of the flapping wing gives way to a Reynolds number-dominated flight regime in which flapping wing structures become paddle-like appendages that “swim” through the air as opposed to relying upon aerodynamic lift. To the tiniest of flyers, the thrips (*Thysanoptera*: weight = micrograms, wing span = ~2mm), air is like a thick fluid through which it propels itself on feather-like wings (Figure 3).

Figure 3. The thrip Thysanoptera at Reynolds Number of 10.

It is apparent then, that biological entities can propel themselves with flapping flight in a range of environmental conditions common to Earth, including gravity, air density, and temperature, however their size is bounded on the upper end by actuator (muscle) strength.

Other factors affecting the ability of a biological entity to maintain sustained flight pertain to efficiency of the propulsors (wings), energy conversion, and energy density. High energy fuels must be converted efficiently into motion of the propulsors. As recounted above, hummingbirds can ingest nearly three times their body mass in nectar per day to sustain life and mobility. [6, 7] Given that the energy is of sufficient density, how efficient is its conversion to motion? One benchmark test in which the wing muscles of wasps were observed through an opening cut in the cuticle of the thorax during flight revealed that contraction and expansion of the muscle fibers only accounted for two percent of the overall muscle length during each full beat of the wing. [11]

Another benchmark measurement has been reported in the literature in which the muscle efficiency and level of resonant energy storage has been estimated for the fruit fly Drosophila *hydei*. In this study, the mechanical efficiency of the flight muscle was determined to be only ten percent, while the energy stored elastically for resonant release was estimated to be somewhere between 35 and 85 percent. [12]

The design of machines mimicking biological entities will fare no better than their analogs, so a performance boundary is set by that observed in nature. Whether this boundary is an upper limit or a lower limit will be determined by the ability of the designer to come up with mechanisms not found in creation, but which can be applied to an otherwise biologically-inspired machine. Mankind has been able to exceed the biological flight envelope in the areas of speed and altitude for example, but across the board, no machine has yet to match the overall performance observed in natural systems (navigation, endurance, precision and agility, self replication, energy harvesting to name a few areas in which biological system excel and exceed all man-made designs).

Being able to replicate the mechanisms of biological flight in a machine requires an understanding of the underlying kinematic and aerodynamic principals of the flapping wing. From there simulations of the flight aerodynamics and later the higher behaviors such as stability and control, navigation, and specialized maneuvers such as perching can be implemented in a flying machine of similar scale.

3.0 MODELING OF SMALL FLAPPING WING AERODYNAMICS

Although flapping wing flight is the only form existing in nature and was the major motive in the initial advancement of flight, the highly complex nature of bird and insect kinematics has hampered the general understanding of this flight regime. A broad level insight is being presented here, which can serve as a basis for future analysis and study. Before detailing the aerodynamics of the flapping wing, it is appropriate to discuss conventional fixed wing and rotary wing aerodynamics.

The basic concern in steady state flight of fixed wing aircraft is the balance of four forces: lift, drag, thrust, and gravitational force of the vehicle weight acting towards the centre of Earth. In steady state forward flight lift has to balance out weight, and thrust must overcome drag to produce steady flight with forward velocity. In the case of unsteady flight conditions, the force imbalance results in an acceleration term. In addition to this force balance, a moment balance is also required, which is achieved by control surfaces that also provide net forces for stability and maneuverability.

In the case of rotorcraft, the main rotor is responsible for producing a resultant force, which will balance out weight during the hover condition. In forward flight, the thrust vector from the main rotor is tilted forward to provide a force component in the forward direction that will balance out the net drag and weight. The case of a rotor craft more closely resembles that of a flapping wing, as it is also unsteady, and the blade flap angle and pitch angle (feathering) changes along the plane of revolution. The “collective control” is used to increase or decrease the angle of attack of all rotor blades simultaneously. However, “cyclic control” is used to increase the angle of attack at one azimuth value while decreasing it 180 degrees around the rotor disk plane. Since there is an associated phase lag, the rotor blade flaps after 90 degrees (in the case of no hinge offset), and rotorcraft accelerates or decelerates in forward flight. The tail rotor is used to balance main rotor torque in a conventional helicopter configuration.

There are basically two sources of these aerodynamic forces, pressure distribution and shear stress distribution. The integral of these two forces will result in the net forces of lift and drag, where lift is defined as force perpendicular to flow velocity, while drag is defined as being parallel to the flow. Depending upon the level of fidelity desired, different techniques are used to compute these aerodynamic forces, which are as follows:-

- Based on the thin airfoil theory, the lift curve slope of a two dimensional airfoil is assumed as 2π, and then depending on the angle of attack (angle between airflow and chord line), the lift coefficient can be computed. This lift coefficient is a non dimensional number which is based upon surface area of the wing and dynamic the pressure that can be converted into a net amount of lift. If the weight of the aircraft is known, we can compute to the first order, the area of the wing required to lift the aircraft. This calculation is insufficient for used for wing design, as it does not take into account the planform shape and airfoil shape.

- The second method is based on the planform shape, in which the wing is divided into small segments, and based on the angle of attack for each segment and lift curve slope for the individual airfoil shape, the lift of each segment can be computed. Then all the segments can be numerically integrated to calculate the lift of entire wing. In this method, the effect of taper and twist are accounted for in each segment.

- The third and the more precise technique is the “lifting line method” for high aspect ratio wings and “lifting surface method” for low aspect ratio wings. In these methods the wing is replaced by a lifting line or lifting surface with bounded circulation at each segment and any wing tip vortices and trailing edge vortices. Whenever there is a change in flow condition such as angle of attack or flow velocity, a vortex is shed. These shed vortices initially begin as a starting vortex and all subsequent shed vortices reach up to the starting vortices. According to the Biot Savart law, all of these vortices result in a downwash or induced velocity at the lifting line, which act to reduce the effective angle of attack of the airfoil.

$$\alpha_{eaa} = \alpha_{gaa} - \alpha_{iaa}$$

where

α_{eaa} =Effective Angle of Attack
α_{gaa} =Geometric Angle of Attack
α_{iaa} =Induced Angle of Attack.

The downwash angle and change in circulation along the span results in induced drag on the wing. The lift produced by a segment is related to the circulation by the Kutta Joukowski Theorem

$$L = \rho \bullet V \bullet \Gamma$$

where

L = Segment Lift (2-Dimensional)
ρ =Air Density
V =Air Velocity
Γ =Circulation (2-Dimensional)

The effects of vortices, downwash, and associated velocities can be seen in Figure 4. [13] In rotorcraft there are continuously shed vortices, as flow velocity and angle of attack vary continuously along the planes of blade rotation and blade flap. Also there is a rolling moment due to the force difference from one side of the rotor to the other. To alleviate this rolling moment, hinges are used at the root of the blade to allow it to flap up and down. The simultaneous flapping, rotation, and feathering results in aerodynamic forces, centrifugal forces, and inertial forces. The moment balance due to these forces dictates the kinetics of rotor blade.

Flapping wing flight shares the kinetics of both fixed and rotary wing aerodynamics in addition to a few aspects peculiar to flapping wings. The basic motions found in the flapping wing flight of birds and insects are:

- Flapping with certain amplitude and frequency.
- Pitching or Feathering along with the flapping motion.
- Spanwise extension or retraction (folding & unfolding) of wings.
- Aeroelastic deformation of wing surface to cope with the aerodynamic loading.

As with rotary wing flight, each azimuth position of the blade (wing) can be discretized all along one blade revolution (flap). The blade flapping motion could also be discretized at different points along the flap motion. Depending on the fidelity, each upstroke and down stroke can be discretized at different points and then forces can be numerically integrated over a complete flap cycle (period) and averaged.

Along with the flapping motion, there is an associated pitching motion that also varies along the flap cycle. The Figure 5 describes the motions in a flap cycle. [14]

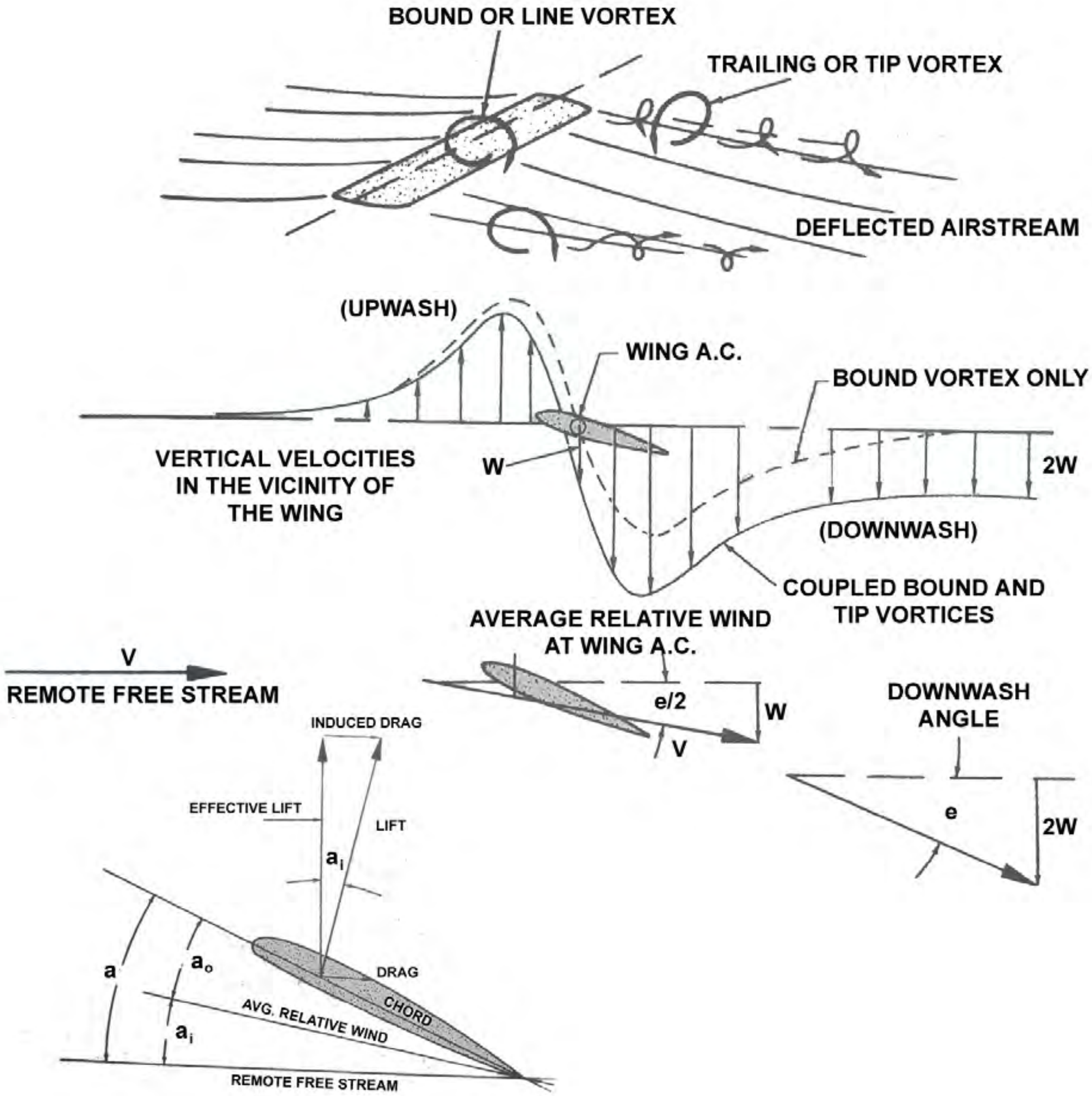

Figure 4. Effect of vortices and downwash. [13]

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The motion described in Figure 5 is a flapping motion where there is a phase angle of 90 degrees between pitching and flapping. Pitching is also continuous like flapping, but there can be cases such as hummingbird flight, in which changes in angle of attack only occur at the extremes of the upbeat and down beat to result in the motion depicted in Figure 6. [15] This is not only easier to implement in a physical system, but would also be easier to simulate.

Since flapping requires less aspect ratio due to structural limitations, lifting surface theory shall be used as a basis for analysis. At any discrete wing location, the presence of the wing in the airflow will cause vorticity in that flow. This vorticity then results in a circulation, which can be determined at different points along each two dimensional airfoil section, If the wing is divided into different panels, with each panel having a certain value of bound circulation, and we consider there to be wing tip vortices, then the effect of the wing tip vortices and trailing vortices which exist due to different bound circulation along the span, will cause a downwash aft of the wing. This results in a reduced effective angle of attack, and is similar to a the effects experienced in a fixed wing airplane.

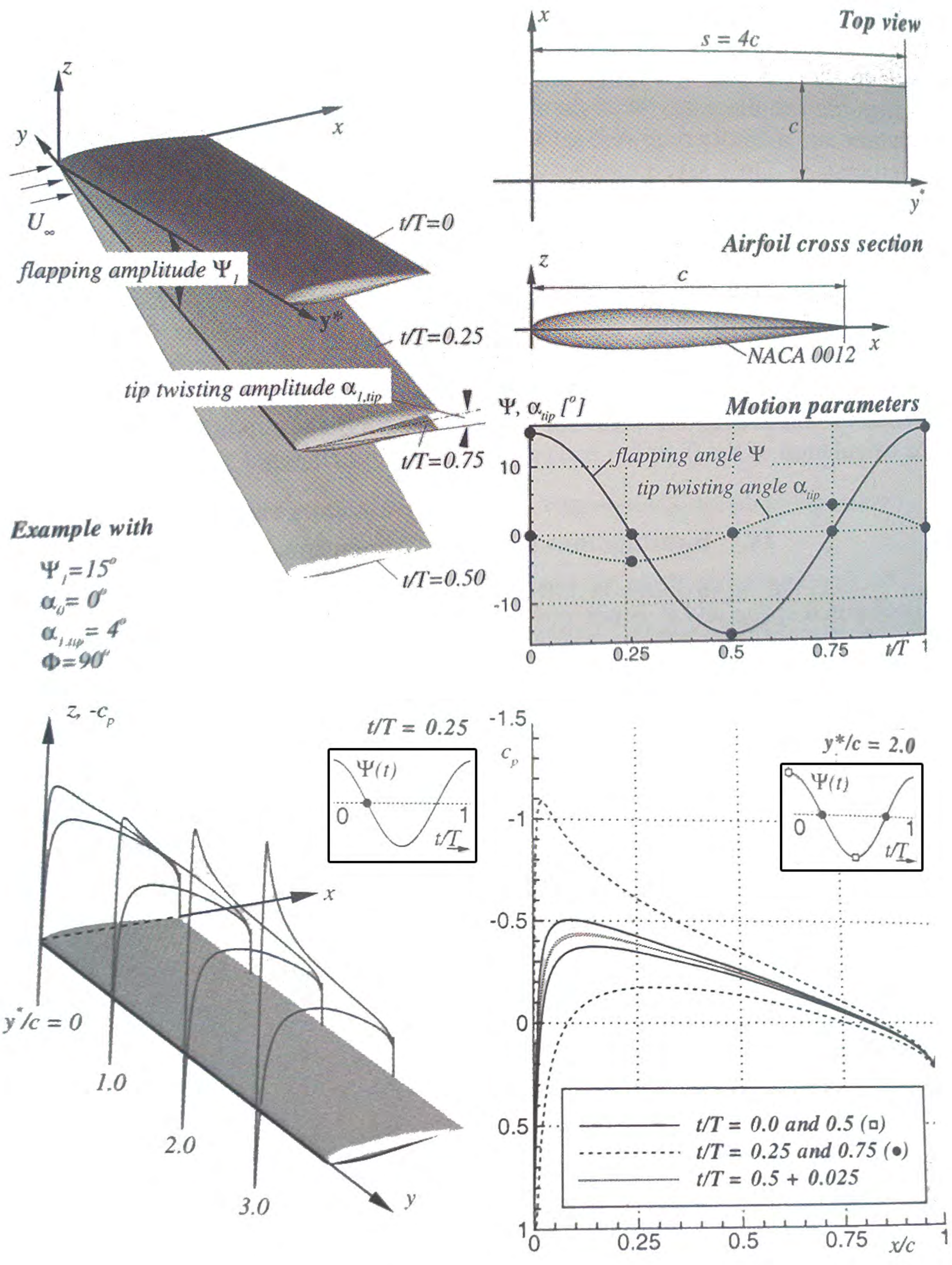


Figure 5. Flapping Dynamics. [14]

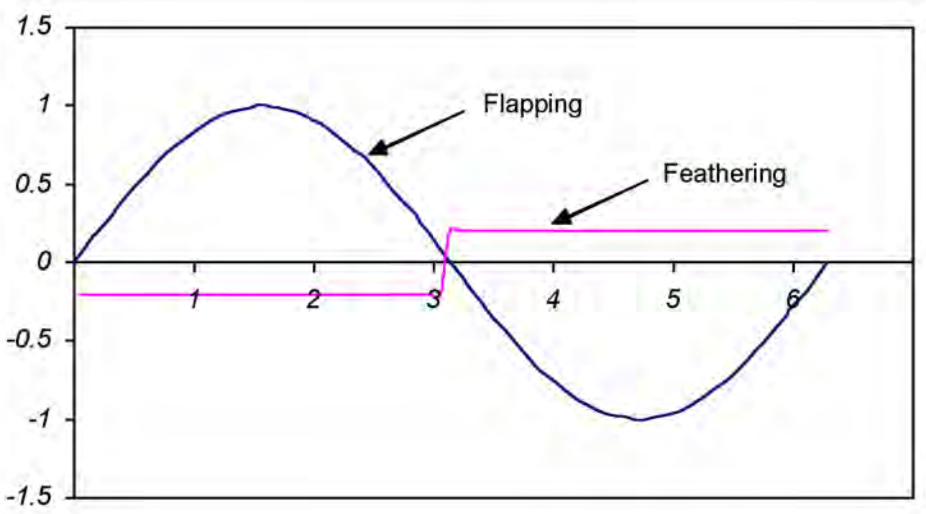


Figure 6. Pitch and flap change humming bird.

These vortices also exist in a fixed wing flight scenario, hence at every discrete point, one might consider a flapping wing as a fixed wing, but the problem is complicated by the presence of shed vortices. Whenever there is a change in angle of attack or flow condition, there is a shed vortex equal in strength to the change in strength of bound vortex, but opposite in sign. These shed vortices are shown in Figure 7. Many researchers [16] have predicted that these shed vortices play a significant role in thrust generation for flapping wings.

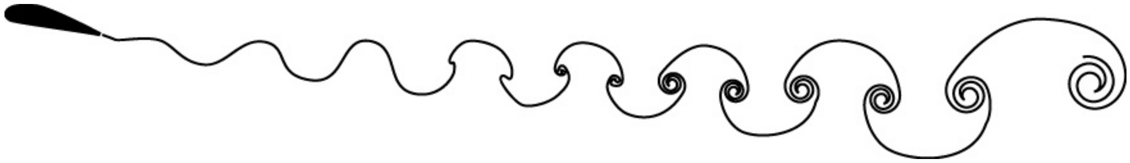


Figure 7. Shed vortices following a change in lift force .

All these vortices, according to the Biot Savart law, result in a downwash velocity. Now consider the different velocity components present in a flapping wing flight which are as follows:

- There is a flapping velocity perpendicular to the wing, which is varying in upstroke and downstroke, with zero at extremes and maximum at the center just like a pendulum motion. Also this velocity will vary all along the span from zero at root to maximum at tip of the wing.

$$V = r \bullet d\beta/dt$$

where

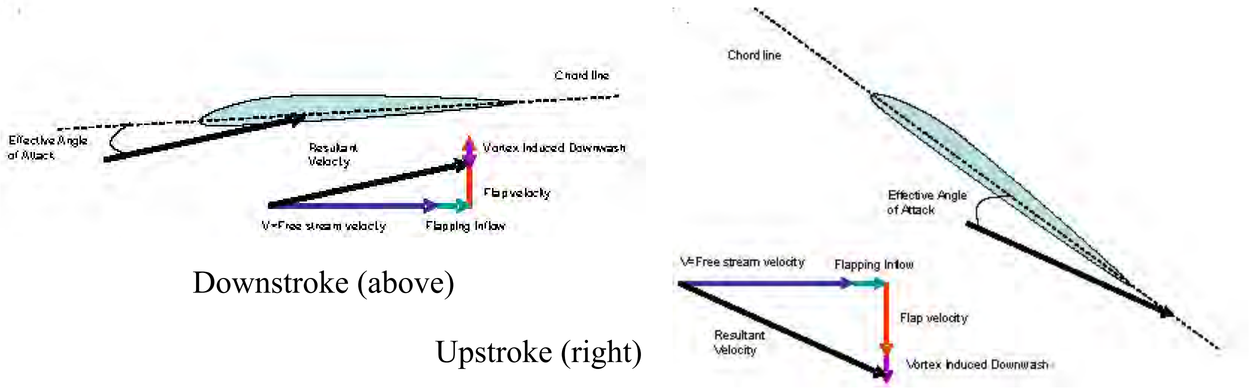
V = Velocity due to flapping motion
r = Span location
β = flap angle
$d\beta/dt$ = rate of change of flap angle

- In addition to this velocity, there is also an induced velocity just like the induced velocity of a propeller or rotor. This induced velocity is perpendicular to the flapping motion. This velocity component creates an inflow velocity perpendicular to the flapping in the direction of free stream velocity. This velocity component also varies along the span position and can be found by using vortex theory or “combined blade element momentum theory for rotors”. The effect of downwash due to wing tip vortices, trailing vortices, and shed vortices is included.

- Free stream velocity.

- If the feathering is taking place all along the flap cycle as shown in Figure 5, there will be a velocity component perpendicular to the free stream due to this steady feathering. But as discussed earlier, it can be assumed that feathering takes place at the extremes, and change is instantaneous (thereby simplifying any analysis).

These velocities then add up to make a resultant velocity, which is used for aerodynamic forces calculation. Figure 8 shows all of the individual velocity components and the resultant velocity. It can be seen that velocity is coming from the upside during the upstroke, and coming from the downside during the downstroke. [17] The angle of attack is positive for both the strokes, and induced velocity must be reduced to increase the effective angle of attack and hence resultant force. It must also be constant to avoid any changes in circulation along the span and trailing vortices. So the basic analysis of these individual velocities and the resultant velocity as a function of time into the flapping cycle, angle of attack, and flapping angle as a function of time can be calculated. By knowing these things, we can compute the aerodynamic lift force, thrust force, and drag.



Downstroke (above)

Upstroke (right)

Figure 8. Velocity components in downstroke and upstroke

The above methodology allows us to compute the aerodynamic forces at one discrete flap position. This can be integrated over time to get the average values over a flapping cycle. It can be shown that the lift and thrust produced at the low flap frequencies used by birds and insects are not enough to sustain flight, so there must be other aspects of flapping flight which are not accounted for in the previous analysis. In fact if the resultant aerodynamic, centrifugal, and inertial forces are considered, there are components of forces and flow along the wing span also. Once this spanwise flow interacts with the bound circulation along the span, this results in a bounded leading edge vortex (LEV). This leading edge vortex, is a major contributor of lift and thrust, especially in insect flight. [18]

The formation and dissipation of leading edge vortices, trailing edge vortices, and axial flow during a wing flapping cycle is shown in Figure 9. [adapted from 19]

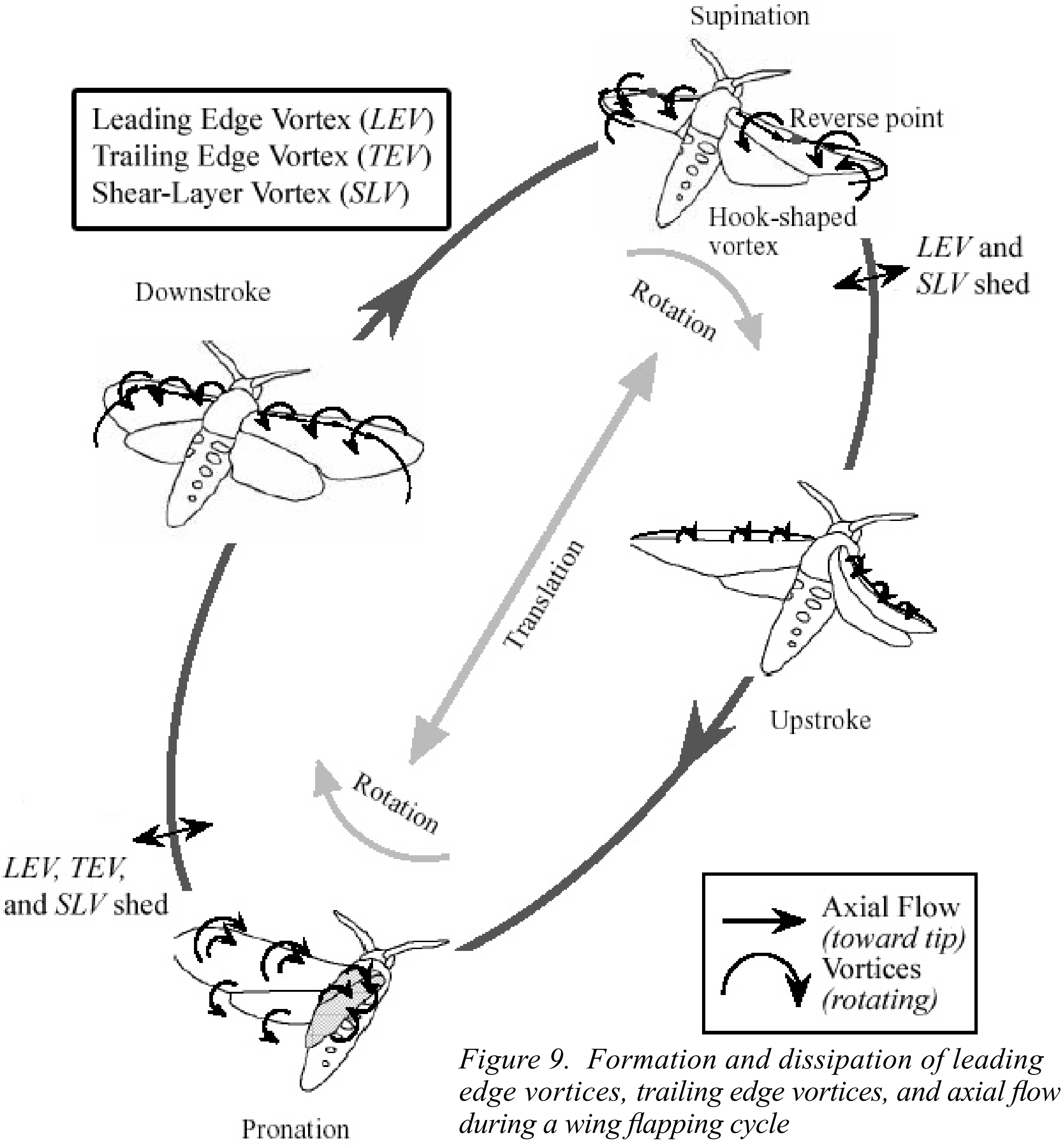


Figure 9. Formation and dissipation of leading edge vortices, trailing edge vortices, and axial flow during a wing flapping cycle

During most of the downstroke, a bounded spanwise vortex is detected at the leading edge, however this is not very significant in the upstroke. The effect of leading edge vortex presence acts as tremendous increase in airfoil camber and hence high values of lift. [19] Researchers have performed testing on various insect wings and found that 80% of the lift is produced in the downstroke and later part of upstroke, mainly due to the existence of leading edge vortex. The high increased camber can also be viewed as operation at very high angles of attack, which are much greater than the stall angles, hence dynamic stall exists in the flap cycle. C_L values in excess of 3 are easily achievable in flapping flight of insects, because of the leading edge vortex and dynamic stall.

More so in birds than insects, folding and unfolding of the wings is employed during the flap cycle. Extension to full span (increase in surface area) in portions of the cycle where positive lift is produced helps to increase the net force, while folding or retracting during parts of the flap cycle where negative lift is produced reduces the net force to make the flapping more efficient. Also by employing an adequate spanwise twist distribution that varies with flap angle, a bird or insect can reduce the induced velocity and hence induced drag.

So far the force balance has been all that has been considered, but if we include moment balance, we will find that a net pitching moment exists that must be alleviated. Either there should be a lead-lag hinge mechanism, or the wing should not be rigid and should be allowed to deform under the aerodynamic load. This phenomenon of aeroelastic deformation exists in flapping wing flight. [20] At every discrete flap position, we can apply the Kutta Joukowski Theorem and then apply the Kutta condition at the trailing edge as boundary condition, but since the trailing edge is deforming, boundary conditions will also be different for every discrete flap position. Hence the solution would require iteration at every discrete position chosen thereby making the analysis even more computationally intense.

To summarize, the following things are changing during the flap cycle:

- Flap position
- Flap rate
- Pitch angle or feathering (during the entire cycle or just at the extremes)
- Flapping induced velocities
- Downwash velocity due to vortices
- Surface shape to account for moments
- Bound circulation on the wing surface
- Axial flow and axial forces
- Leading Edge vortex shape and strength
- Dynamic stall phenomenon

Lift and thrust forces were the point of emphasis in the preceding paragraphs, but the actual problem concerns how efficiently one can generate this lift and thrust, that is, with minimum drag. The drag consists of profile and induced portions. Depending on the Reynolds Number value associated with the flight condition, the skin friction component of drag can be determined, but pressure drag will vary based on the flap position and the pressure distribution at that specific flap angle. Depending on the Reynolds Number, flow will be either laminar or turbulent, and will define the boundary layer and separation if it occurs. In flapping wing flight things are different from conventional fixed wing flight in that the boundary layer separates at much lower angles of attack for the flapping wing. Also transition to turbulent flow occurs much earlier. The separation causes an adverse pressure gradient and reduces the value of lift produced while increasing the pressure drag. The net drag produced in the turbulent boundary layer at low Reynolds Numbers is less than the drag produced in a laminar boundary layer.

Another concern in flapping wing flight is the stability and control. Fixed wing aircraft have control surfaces which are not present in insects while the tail in birds produces very little control force compared to that provided by the differential lift of the two wings. This makes the flapping wing design even more challenging. Lateral and roll control is provided by impaired lift from side to side while pitching control is provided by increased feathering for climb and decreased feathering amplitude for descent. Wing location longitudinally and laterally at the fuselage/main body will govern static stability.

After the analysis of all the elements described above, the average values of thrust, lift, and drag can be computed over a flap cycle. These values can be translated depending on the velocity and flapping parameters to compute the power required for controlled flight. It has been found [21] that apart from the efficiency of the motor (gas turbine, muscle, etc.) the power required in flapping wing flight is much less than that for the conventional fixed wing airplane.

Another important aspect of flapping wing flight is the amount of harmonic content present in the flapping dynamics. Once moment balance equations are written, moments due to aerodynamic forces, centrifugal forces and inertial forces must balance. Aerodynamic moment is just a function of flap position and pitch position, centrifugal moment is a function of flap rate and pitch rate, while inertial moment depends on flap acceleration and pitch acceleration (pitch means feathering i.e., change in angle of attack). There is a phase lag associated with flapping and pitching (depending on that phase lag, amplitude, flap and pitch frequency), flap and pitch positions can be defined in terms of time and respective frequencies. In order to avoid any unwanted vibrations, at least 2nd order effects must be included in any Fourier series expansion.

For example,

$$\beta(t) = \beta_o + \beta_{1c}\mathrm{Cos}(\Omega_f t + \beta) + \beta_{Is}\mathrm{Sin}(\Omega_f t + \beta) + \beta_{2c}\mathrm{Cos}(2\Omega_f t + \beta) + \beta_{2s}\mathrm{Sin}(2\Omega_f t + \beta)$$

where

β = Flap Position as a function of time t

$\beta_o, \beta_{1c}, \beta_{Is}, \beta_{2c}, \beta_{2s}$ = Flapping coefficients

Ω_f = Flapping frequency

β = Phase Angle

The system is analogous to a spring-mass-damper system, and once some forcing function like external gusts or vehicle initiated control is applied, the response will have higher order terms, which must be balanced in order to have low harmonic content.

All the above discussion up to this point has been focused on the analysis of an existing geometric configuration. It indicates the types of contributions that must be considered in the analysis to estimate the aerodynamic forces and moments, and helps to estimate the control power and moments required for a specific change in flight conditions. The simulation of all the above effects will help evaluate the specific design configuration and its response to external variables like flapping and pitching frequencies and the lag between them. But the above model will not suffice for the requirements of a generic design tool. In nature, hundreds of thousands of species employ flapping wings, and all of these use distinct features to optimize their performance to specific needs. Some use less flap amplitude with a higher flap frequency, while others use more amplitude and lower frequency. Similarly some use variable feathering all along the flap cycle, while others change the angle of attack during the last ten percent of their strokes. To design a numerical tool which could assess all different configurations is beyond the current understanding and computational capabilities presently available.

However, a design tool can be designed which takes into account a point configuration, but has the capability to account for changes in different geometric variables, environmental variables, and operational variables. Efforts are ongoing to formulate such a numerical tool. [22] The basic infrastructure would include the following:

- An analysis tool with adequate fidelity to encompass all the aerodynamic analysis of forces and moments described above.

- Based on the number of control variables and noise variables, use a “design of experiments” to form an orthogonal array of simulations in order to capture the different areas of the design space.

- Simulations in the selected “design of experiments” array will be performed, and responses calculated using performance parameters such as lift, payload, endurance, etc.

- Response surface equations can then be regressed to the data available from the “design of experiments” to aid in understanding the effect of different variables in response to the variability of responses.

- If deemed necessary, even a probabilistic evaluation could be performed to find out the feasible design space regions in which all system constraints are met.

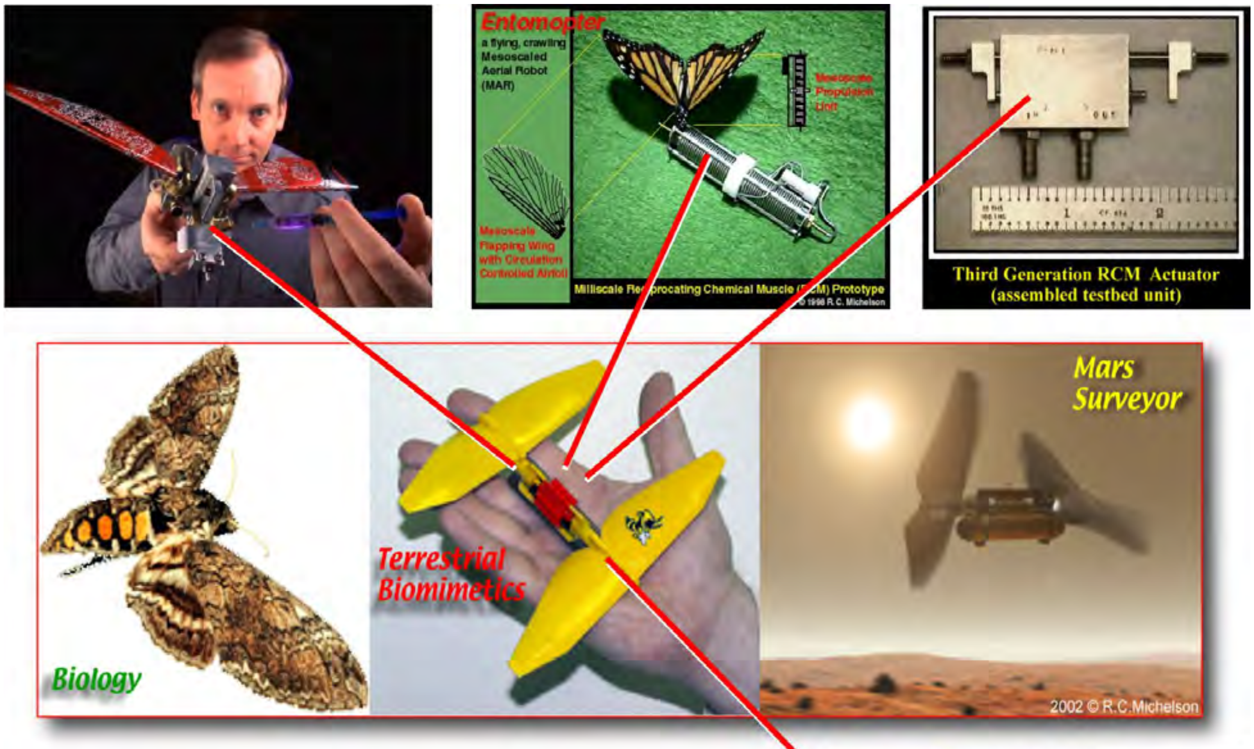
- The response surfaces equations will not only help in understanding the effects of different variables, but can also help optimize the configuration for any specific performance goal, like maximize range or maximize endurance.

The above design tool can be further improved by making the initial analysis tool a “multidisciplinary analysis”, wherein aerodynamic consideration might be used to optimize wing planform to minimize drag and maximize the lift-to-drag ratio. This would give different spanwise twist and feathering distributions in a flap cycle, while control considerations might improve the control sensitivities by either increasing the control power, or reducing the control damping. Similarly structural analysis might focus on weight reduction and employment of different structural constraints that could conflict with control and aerodynamic considerations. Propulsive analysis could lead to minimum size and energy consumption, but will impose size constraints for structural aerodynamics and weight constraints. All of these different disciplines will have their respective codes and optimization goals. The codes for different disciplines can be nested into the multidisciplinary analysis tool, which can be analyzed and optimized by different Multidisciplinary Design Optimization techniques.

4.0 EXAMPLE DESIGN GOING BEYOND BIOMIMICRY

An example of a MAV that demonstrates high degrees of innovation, extreme integration, and biological inspiration is the Entomopter. It embodies the ten principals outlined in Section 1.0 and is described here as one example of how these principals can, and have been, applied to a MAV system.

The terrestrial Entomopter has been designed for indoors operation where its small size (15 to 18 cm wing span) would actually be an asset. This generic mission calls for a highly maneuverable slow flying vehicle capable of obstacle avoidance in close quarters. The design process began by asking “what configuration could best meet these requirements?” Fixed wing approaches were eliminated due to their speed, which made obstacle avoidance, landing, and taking off again problematic. Lighter-than-air approaches could not carry adequate payload for vehicles in the 15 cm size range. Rotary wing approaches although feasible, were determined to be inferior to flapping wing designs because of acoustic signature, lack of robustness (rotors striking objects do not survive and lose weight efficiency if shrouded), and the inability to conserve energy through the application of resonance. On the other hand, flapping wings have been observed in indoor environments on many occasions where birds and insects have invaded living spaces. These biological entities fly almost silently, can sustain a wing strike with objects (walls, ceilings, etc.)



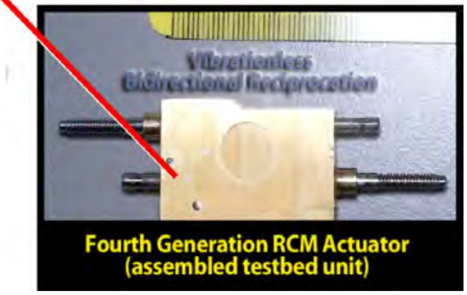


Figure 10. Generations of the Reciprocating Chemical Muscle Actuator.

and survive unscathed, while being agile enough to avoid obstacles and even perch when necessary. Flight reinitiation from a stationary posture is also observed.

The 'Entomopter' (*entomo* as in entomology + *pteron* meaning wing, or a "winged insect machine") began not as an air vehicle, but as a propulsion concept once a flapping wing solution had been adopted as a general system architecture. The Entomopter is a multimode autonomous robot capable of flight, ambulatory locomotion, and swimming behaviors in a single vehicle (see Figure 10). Autonomous navigation is based on a combination of attraction and avoidance behaviors deriving input from both an integrated optic olfactory sensor for detection and tracking of chemical species (or, alternatively, a sensor for a specific type of radiation), and an ultrasonic swept beam ranging device. Since the flapping wing was chosen as the best approach for flight, the other modes of locomotion (crawling or swimming) were based on the same actuation system as that used for flapping wing flight, but do not involve the complexity, precision, or energy expenditure associated with flight.

Terrestrial Entomopter feasibility was established under contract to the DARPA Defense Sciences Office Mesomachines Program, where it is referred to as a Mesoscaled Aerial Robot (MAR). NASA recognized the Entomopter's ability to fly in low Reynolds number conditions without the need for air-breathing propulsion made it a natural candidate for flight in Mars' rarefied atmosphere. Unlike fixed wing flyers, an Entomopter-based Mars surveyor would be able to cover a wide area while still being able to fly slowly, land, crawl, obtain surface samples for analysis, and return to a refueling rover.

The Entomopter began as a biologically inspired design, but rather than attempting to replicate biological kinematics and aerodynamics, improved systems have been devised to leverage what is observed in biological systems to produce a machine that is manufacturable, controllable, and able to generate the power necessary to fly from onboard energy sources. Thus, the Entomopter design has been extended beyond the biological baseline in some areas.

The Hawk Moth (Manduca *sexta*) was chosen as a baseline model for the wing aerodynamics. The University of Cambridge in England was part of the initial Entomopter design team because it had studied Hawk Moth wing aerodynamics for more than a quarter of a century and had produced seminal works describing the Leading Edge Vortex and its effects on the flapping wing [23, 24, 25, 26, 27]. The flapping mechanism for the Entomopter has been extended beyond that of the Hawk Moth to provide a resonant single-piece “X-wing” construction that takes advantage of torsional resonance in the Entomopter fuselage to recover flapping energy as is common to flying insects which temporarily store potential energy in either muscles or exoskeletal parts (resilin).

A chemically fueled reciprocating chemical muscle has been designed and is in its fourth generation of development at the time of this writing. This actuator system has demonstrated 70 Hz reciprocation rates with throws and evolved power levels necessary to support flight, crawling, or swimming of a self-contained fully autonomous Entomopter system [28]. The reciprocating chemical muscle uses the energy locked in various chemical fuels to produce reciprocating motion for propulsion as well as waste gas products for the operation of gas bearings, an ultrasonic obstacle avoidance ranging system, and full flight control of the vehicle. In all, precious and limited energy stored onboard this 50 gram MAV is used up to seven times before it is released. These uses are:

4.1 Energy Use 1. A regenerative muscle that consumes various fuel types in a noncombustive process that yields forces and frequencies consistent with flapping wing flight at the scale of a 15 cm MAV.

4.2 Energy Use 2. Reuse of muscle waste gas for circulation-controlled lift modification of each winglet independently, thereby allowing stable flight as well as the ability to change heading for navigation. Stability and control in flight as well as navigation are achieved by actively modifying the lift of each wing on a beat-to-beat basis using pneumatic control of both the laminar flow and the leading edge vortex circulating over the beating wing. As such, the Entomopter is *not* a synthesis of a flapping wing and an airplane tail. It derives all of its lift, thrust, AND control from its wings alone, and it is simple enough to be manufactured affordably.

4.3 Energy Use 3. A steerable beam frequency modulated continuous wave (FMCW) acoustic obstacle avoidance system that uses waste gas from the muscle and wing motion to sense both altitude above the ground and obstacles such as walls. The FMCW transmission capability is inherent in the muscle at no energy cost. The same structure that provides wing flapping also scans the FMCW ultrasonic beam to provide front, side, and down-looking range measurements for obstacle avoidance and altimetry. Further, this ranging design has the potential to track and follow free-moving agents in a fashion similar to that employed by bats.

4.4 Energy Use 4. A limited amount of onboard thermoelectrically-generated electric power derived from muscle waste heat resulting from the controlled exothermic decomposition of the fuel that can be used for the obstacle avoidance receiver electronics and onboard intelligence.

4.5 Energy Use 5. A mass flow amplifier based on an ejector to supply higher volumes of lower pressure, cooled gas for use in circulation control of the wings.

4.6 Energy Use 6. Gas bearings for all moving mechanical interfaces. No wetted surfaces or lubricants are required because waste gas is used as a bearing surface.

4.7 Energy Use 7. Directional thrust. If sufficient energy remains in the waste gas, it can be expelled intelligently to provided a degree of directional thrust for launch assist, breaking, or maneuvering in flight.

5.0 SUMMARY

This paper addresses the challenges encountered during the design of miniature flight platforms, with particular focus on the most interesting and potentially useful class of micro air vehicles that are biologically-inspired. Beyond low Reynolds number aerodynamics and extreme miniaturization, the micro air vehicle designer must address high levels of system integration, efficient use and reuse of energy, and systems that can be physically and affordably manufactured once designed. Since the act of flying is the most energy intensive function for a biologically inspired micro air vehicle, a discussion of the basic principles of flapping wing flight at small scales has been presented. Understanding of the unsteady aerodynamic principals involved is essential if the design is to progress beyond mere biomimicry to an advanced solution that leverages the biology while accommodating the practical problems of energy management and simplicity of implementation. The Entomopter is an example of the high degree of innovation required to make practical miniaturized flying machines on the scale of small birds and insects. Leveraging biologically inspired mechanisms such as flapping wings, crawling, and echolocation, the Entomopter does not stop at mere biomimicry, but goes beyond to improve upon these natural systems with torsional X-wing flapping, circulation control of wing aerodynamics to achieve additional lift, thrust, and control through a single mechanism.

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