Experimental Design of a Flapping Wing Micro Air Vehicle through Biomimicry of Bumblebees

Michael Thompson[*], John Burnett, [†] Akshay Batra, Deyzi Ixtabalan, and Diana Tran[‡]
Dr. Armando Rodriguez[§], and Dr. Bruce Steele [¶]

Arizona State University, Tempe, AZ, 85287, United States

The main focus of this research was on the aerodynamic characteristics of a Bumblebee Micro Air Vehicle (BMAV) recently developed at ASU. The BMAV prototype has a flexible membrane with an aspect ratio of 4.18 and a chord of 8 cm. The aspect ratio of a typical queen bumblebee is 5.78.[1] One wing area is 90.38 cm^2 measured from the SolidWorks model and an inner area-fuselage of 6.78 cm^2. The planform area, S was calculated as 187.56 cm^2. Since MAVs typically fly at low Reynolds number (Re), a Reynolds number of approximately 63,000 (12 m/s) was used for wind tunnel testing. The dynamic wing behavior is able to articulate in two degrees of freedom; i.e. a figure 8 rotational flapping pattern characteristic of many insects. The wing span, b of the prototype is 28 cm. The current BMAV model was designed through SolidWorks and manufactured using 3D printing to build a rapid prototype. The rapid prototype replicates an actual bumblebee, mimicking the insect's articulation for its aerodynamic attributes. The BMAV prototype has a 12 volt, six winding brushless motor with a maximum speed of 8,750 rpm. The motor provides hovering equilibrium which presented a persistent challenge in previous prototypes. Experimentally, from wind tunnel tests, the lift coefficient was found to be 0.5894. The stall angle was observed at +16 degrees angle of attack, α. The minimum drag coefficient was observed to be -0.2389 at an α of -7 degrees. The collected experimental data permits a computation of aerodynamic derivatives that will be used in the near future to model the micro air vehicle within future nonlinear 3DOF/6DOF MATLAB/Simulink simulators.

α	Angle of attack, deg
C_d, C_l	Drag and lift coefficient
D	Drag, N
L	Lift, N
P	Pressure, Pa
ρ	Density, kg/m^3
V	Velocity, m/s
x, y, z	Cartesian body axes, m

I. Introduction

Micro air vehicles have developed through the years, in different dimensional configurations; however, standard configurations have not been established by the aerospace community.[4,11] Fixed wing aircraft and helicopter blade elements have well established algorithms to predict design efficiency. Flapping wing micro air vehicle designs are typically designed using bio-mimicry.[1,2] Micro air vehicles are rising as the focus of study for multi-functional purposes. Prototypes are being designed to accommodate such purposes

---

[*] Group Leader, working towards PhD in Mechanical Engineering, AIAA member, GEM and NASA Fellow.

[†] Project Engineer, currently working at Honeywell, AIAA member.

[‡] Graduate students, currently working on CFD for Micro Air Vehicles, AIAA members.

[§] Professor of Electrical Engineering, Senior Member, IEEE and AIAA member.

[¶] Laboratory Manager, AIAA member.

as search and rescue and reconnaissance. This work involves developing vehicles with low aspect ratio wings that operate at low Reynolds numbers. The ASU bumblebee micro air vehicle (BMAV) is 6 cm long in direction, 3.1 cm in the chord wise direction, 11.8 cm, with a wing span of 28 cm.

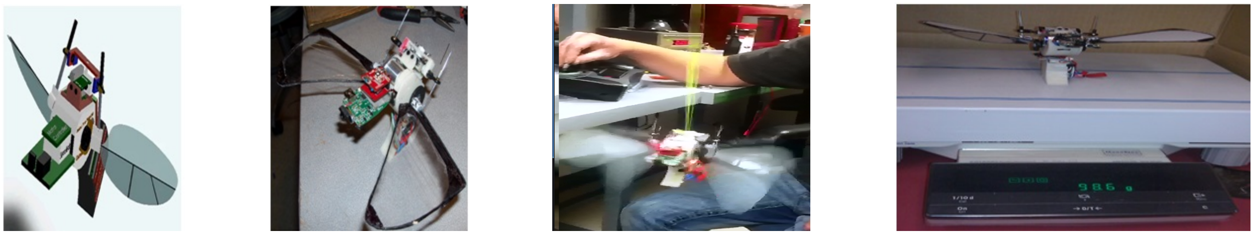
The rotation about an aerial vehicle's center of mass can be analyzed using 3 orthogonal axes: normal, lateral and longitudinal. When the aerial vehicle rotates about the normal axis, otherwise known as yaw, it is rotating around a vertical axis perpendicular to the body of the aircraft. Rotating about the lateral axis is called pitch and is positive "nose" up and negative "nose" down. Finally, rotating about the longitudinal axis, is usually referred to as roll, the aircraft rotates about an axis that passes through the "nose" and "tail" of the aircraft. If the air vehicle possesses all three: yaw, pitch and roll, flight dynamics the vehicle can be said to be controllable and stable in flight.

The BMAV prototype was modeled after a bumblebee's anatomy and wing articulation behavior.[8,9,10] The current MAV design was made through a trial and error process, utilizing many different wing design changes. The current wings were modeled after the wings of a bumblebee, which are more maneuverable than rotary wings.[15]

Based on studies done by Michael Dickinson, biologist and professor of bioengineering at University of Washington, insect flight has immense adaptability when maneuvering.[15] In a short video clip at 7000 frames per second, a fruit fly can reverse its fight path a full 180 degrees after sensing a predator. To comprehend the time frame of the adaptation of the insect's flight, the entire clip is actually the duration of a blink of an eye. How insect wings generate flight, as opposed to aircraft wings, is that they can flap their wings at high α. That high α will create leading edge vortices's, that enable an insect to create enough force for it to maintain hovering stability.

II. ASU MAV Design

Due to the sizing of the MAV capabilities, special attention is required for a range of power and weight; therefore, these requirements must be carefully traded. Much attention is needed in the computational fluid dynamics arena for the MAV wings. This area is one of the utmost concerns because the aerodynamics is least understood in MAVs.[3,4,5] Unsteady aerodynamics play a critical role for MAV flight stability and control concerns.[12,13,14] Typically, MAVs are small in size and weigh below 100 grams.[6,7] The BMAV is approx. 98.6 grams and is made up of carbon fiber spars with a Youngs Modulus of 150 GPa, as seen in the figure below.


(a) The CAE SolidWorks model of the recently designed Bumblebee MAV prototype.

(b) The actual model of the Bumblebee MAV prototype.

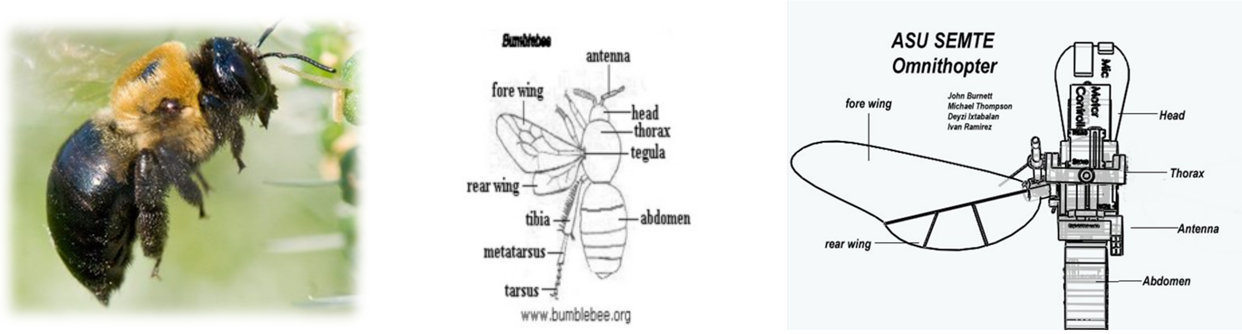
(c) The Bumblebee MAV prototype in flight.

(d) Weighs approx. 98.6 grams with PID controller, camera, brushless motor, Li-PO battery and wings.

Figure 1: ASU Bumblebee MAV prototype, a flexible wing micro air vehicle geometrically modeled, designed, fabricated, and tested at Arizona State University.

The design for our BMAV prototype was made to replicate a bumblebee for its aerodynamic attributes. The BMAV prototype was designed using ABS plastic via rapid prototyping 3D printing. The vehicle uses a brushless motor to increase the lifting capabilities in comparison to a brush-equipped motor. The current BMAV contains 6 Lithium-Polymer batteries. The yield strength of ABS plastic (from the 3D printer) is not suitable for the arm joint of the vehicle due to the compressive stress placed on the joint that causes buckling. Surpassing the yield strength for the arm joint, would introduce deformation and fatigue leading up to possible cracks. Tin was used for the arm joint to withstand the compressive stress.

The manufacturing process of the BMAV prototype exoskeleton and wing assemblies are designed using printing technology and carbon fiber. A MakerBot Replicator 2 was used and in conjunction with a Computer Aided Design (CAD) software package called Makerware. Makerware allowed changes in the parts printing orientation to create a better adhesion in the lay up process. Temperature, part density, number of shells, and print speed, govern the quality and weight of the parts being printed. Issues arising from the parts printer typically involve extruder, nozzle calibration and platform/part adhesion. Adhesion to the platform can be an issue if a bonding pad is not integrated into the part from the SolidWorks model. Part printing technology is used for building all static structural components as well as some dynamic components such as the wing-root, feathering controls and cycloid structure.



(a) A bumblebee

(b) Bumblebee Anatomy

(c) Components of the BMAV prototype

Figure 2: BMAV prototype, a flexible wing geometrically modeled, designed, fabricated, and tested at Arizona State University.

The current BMAV prototype design incorporates insect flight structures for functional wing morphology and evolution purposes to effectively enhance flight performance. In addition to the wing dynamics, the current prototype has no sharp edges and provides a more elegant profile.

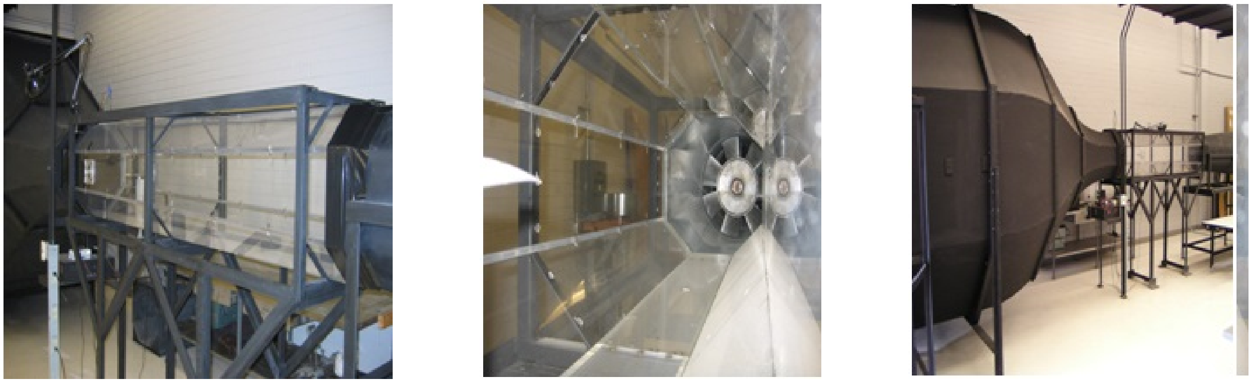
Table 1: Bumblebee MAV prototype Parameters

Parameter	Nominal Value
Wing span	28 cm
Aspect ratio	4.18
Airfoil stall angle	16 °
Max speed	12.88 m/s
Chord length	0.08 m
Area of wing	0.009038 m^2

The manufacturing process for the current BMAV prototype was done by placing screws in the desired pattern for the wing. Then, carbon fiber strands were wrapped around the outside of the screws. Resin was applied to the carbon fiber strands to stiffen the carbon fiber into the desired wing shape. This process was quicker than the previous method of shredding carbon fiber tubes and mixing it with resin, to create the profile of a wing and building it up. By changing the method of producing wings, the entire process has shortened to around an hour, compared to our previous method of about 2 hours. We also purchased 3/32 ″ thick Balsa Wood that was placed around the areas that received higher induced stress concentration. These supports help the wing maintain its shape and reduce the chance of cracking by giving the wing a higher tensile strength.

III. Wind tunnel results

ASU wind tunnel measurements were used to obtain the aerodynamic lift and drag force characterization. The wind tunnel works by flowing air to a a draft fan which pumps in air at high speed (which can be regulated) to a test section, where the BMAV prototype was placed. The wind tunnel has a 30 cm by 20 cm test section with a testing speed up to 20 m/s. The angle of attack for the wing was varied between -10 ° to +25 °. The wind speed was 12.88 m/s. The wind tunnel data provides experimental data that can be compared to validate CFD simulations.

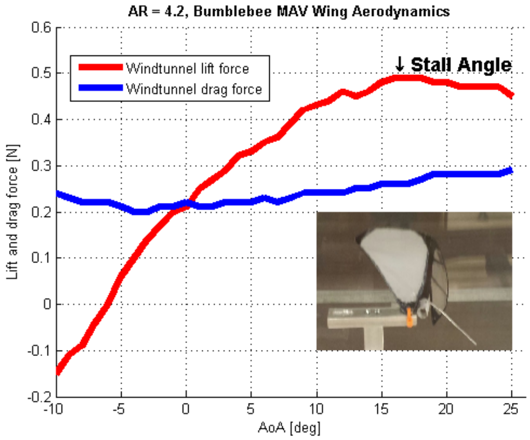


(a) The flow direction of the air in the wind tunnel is from left to right.

(b) The fan inside the wind tunnel.

(c) An overview of the wind tunnel.

Figure 3: The ASU wind tunnel.



(a) Aerodynamic Forces.

Figure 4: Experimental aerodynamic characteristics of the Bumblebee MAV wing from LabView.

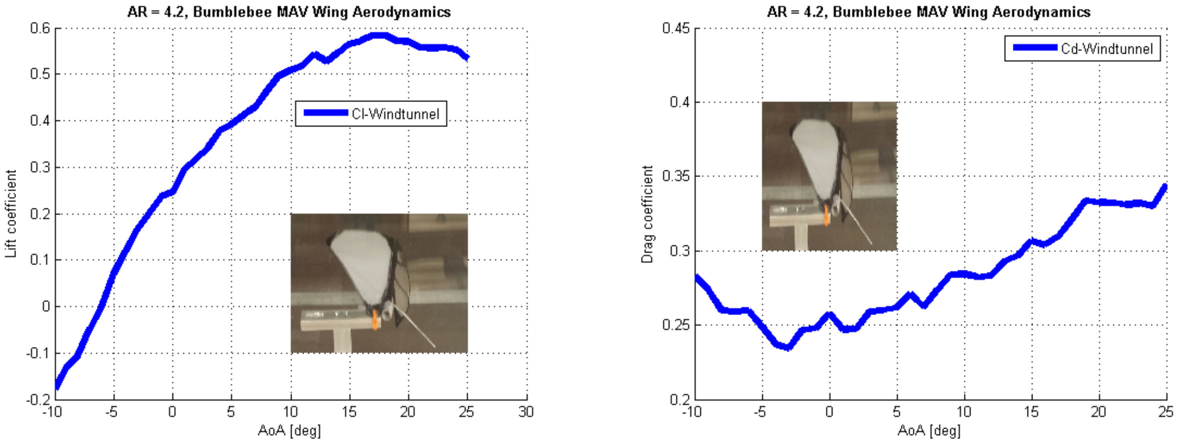
The equations that govern the range of the MAV lift and drag forces Eq. (1), and Eq. (2) may be written as:

$$D = \frac{1}{2}\rho v^2 A C_d \tag{1}$$

$$L = \frac{1}{2}\rho v^2 A C_l \tag{2}$$

C_d and C_l are often assumed constant for simple calculations but a more realistic approach defines them in terms of the α (angle between the wing and the body of its velocity).

The experimentally determined maximum lift and drag coefficients are approximated below by Eq. (3) and Eq. (4).



(a) Lift Coefficient vs α.

(b) Drag Coefficient vs α.

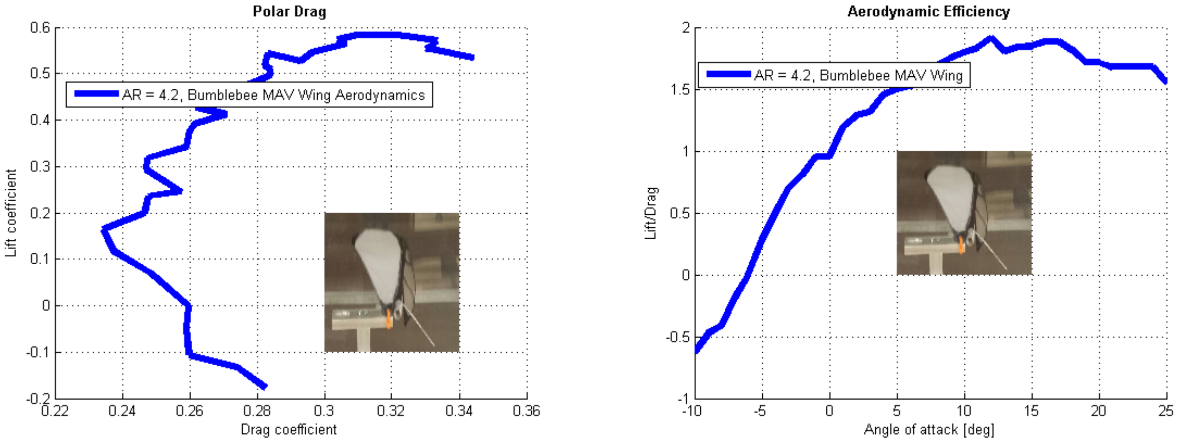
Figure 5: Experimental aerodynamic characteristics of the Bumblebee MAV wing from LabView.

$$C_d \cong 0.24 \tag{3}$$

$$C_l \cong 0.59 \tag{4}$$

Aerodynamic characteristics of the BMAV prototype can be seen from the figures above for the anticipated α range. The lift and drag coefficients are determined by the lift and drag forces. The curves look similar for for other airfoils. The curves exhibit linear behavior near stall α and parabolic behavior after the stall angle has been reached. The curves are comparable to other curves in the literature for MAVs.

The optimum way to approach the flight portion of the BMAV should be to aim for minimum drag in the initial part of the flight and adjust for maximum lift during the flight by changing the body's α.



(a) Polar Drag vs α.

(b) Aerodynamic Efficiency.

Figure 6: Aerodynamic characteristics of the BMAV prototype.

A. Aerodynamic Efficiency

Lift divided by drag is commonly referred to as the L/D ratio. Since lift and drag are both aerodynamic forces, the L/D ratio can be thought of as an aerodynamic efficiency indicator. The figure above shows the aerodynamic efficiency. It can be seen from the figure below that experimentally, the maximum L/D is achieved at +13° α and it is calculated to be approximately 1.94. The wind speed was constant at 12.88 m/s. Poor efficiency results when the BMAV is flying at an angle of attack lower than 0. L/D provides insight into how long a flying body can stay airborne if power is lost.

B. Lift and Drag

From the figure above, the lift results show a linear increase with the α until the stall angle is approached. The BMAV prototype stall angle was seen at +16 ° α where the $C_l \cong 0.59$.

The wind tunnel air velocity blowing from left to right over the wing was low at approximately 12.88 m/s. The wings on the MAV can flap at maximum frequency of 122 Hz from experimental data taken from a tachometer.

Due to the low velocity of the air, the lift coefficient is relatively constant across incident angle. Since the aspect ratio of our BMAV is similar to that of a queen bee, the BMAV prototype may have a high α before it stalls out. For this to occur, low pressure happens at the top surface of the wing and high pressure occurs at the bottom surface of the wing. Due to this pressure differential, the BMAV prototype wing is able to generate lift as can be seen from the experimental data collected.

The stall characteristics for insect wings are abrupt and occur at maximum lift.[9] The lift coefficient declines after this segment partially, from its maximum value. The leading-edge separation bubbles may increase the camber of the wing and prevent stalling.[9] The body lift forces, which act perpendicular to the drag force, may be of significance for flapping wing MAVs, in regards to reducing the net lift of the beating wings.[8] In order to inhibit this stall effect, the wings may be flapping. For flexible wings, wind tunnel data at a stall angle of +20° with an aspect ratio of 2 was reported.[1] The stall angle increases by decreasing the aspect ratio.[1] For insect wings, an abrupt stall angle does not occur.[8,9] This is shown in Figure 5, where after an attainment of maximum lift, typically found in airfoils as an abrupt stall angle, is not seen. Furthermore, for higher aspect ratio wings, it is known to have a higher lift coefficient. In order to fly with minimum drag, the BMAV prototype should have an α of -5° that correspond to $C_l \cong 0.1$ according to the experimental wind tunnel data collected. By increasing the aspect ratio, we obtain a higher lift coefficient.

IV. Conclusion

Aerodynamic characteristics are provided for a recently developed, Bumblebee MAV prototype (BMAV) wing at Arizona State University. Aerodynamic experimental data for the BMAV wings were obtained using the ASU wind tunnel.

It was found that the maximum aerodynamic efficiency for the BMAV prototype is achieved at approximately + 11° α for Reynolds numbers between 62,000 and 63,000. From the experimental wind tunnel data for an α of -10° to +25°, it was determined that the stall angle was at +16°. The maximum aerodynamic efficiency is observed to increase with flying speed. A maximum aerodynamic efficiency occurs at L/D $\cong$ 1.94 and is observed when tested with wind speeds at 12.88 m/s.

The minimum lift force to reach equilibrium must be 0.0096 N for the BMAV prototype to support its own weight. As found through the load cell test, the flapping frequency for the BMAV is capable of flight. The efficiency is due to how the wing articulates and the rigidity of the wing itself. Load cell tests indicate that lift force in hover exceeds its actual weight. A tradeoff between vectored thrust and torque appears to be negating a portion of the force to maintain hovering stability.

Load cell tests were conducted to determine the flapping frequency and lift efficiency for the BMAV prototype. The flapping frequency at quarter throttle was around 16 Hz. The test was performed with a tachometer. The no load test of the brushless motor generated a frequency of 122 HZ which is the flapping frequency of a typical bee. The BMAV had an average of 2.4 N of force from a load cell test. Wind tunnel experiments determined aerodynamic properties such as the max coefficient of drag, $C_d \cong 0.24$ and coefficient of lift, $C_l \cong 0.59$ for upward moving. Additional work is needed to further define aerodynamic characteristics for MAVs. More advanced unsteady aerodynamics (such as unsteady Reynolds averaged Navier-Stokes) are needed to evaluate the performance for MAVs.

V. Acknowledgments

The research in this paper was partially supported by the WAESO-NSF program and ASU facilities.

References

[1] R. Dudley and C.P. Ellington. ”Mechanics of Forward Flight in Bumblebees I. Kinematics and Morphology” J. exp. Biology. Cambridge University Press, 1990. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OmI4MmQyYmNjZDlmNDVlZA

[2] R. Dudley and C.P. Ellington. ”Mechanics of Forward Flight in Bumblebees II Quasi-Steady lift and Power Requirements” J. exp. Biology. Cambridge University Press, 1990. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OmJkMWM3YzQxYTFlODAxZg.

[3] Manoj K.Bhardwaj, ”A CFD CSD Interaction Methodology for Aircraft Wings”, Doctorate Dissertation Virginia Polytechnic Institute, 1997. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4Ojc1NWEwNmRkOWRjYWMzZDA

[4] G. Torres, T. Mueller. Micro Aerial Vehicle Development: Design, Components, Fabrication, and Flight-Testing. University of Notre Dame, 2000. http://www3.nd.edu/~mav/auvsi/torres.htm

[5] D. Gyllhem, K. Mohseni, D. Lawrence. Numerical Simulation of Flow Around the Colorado Micro Aerial Vehicle. University of Colorado. AIAA Fluid Dynamics Conference and Exhibit, Toronto, Canada, june 2005. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjUzNjdkZjFlMmZjNDk3YzQ

[6] Timothy Kinkaides. ”Study of Micro -Sized Technology, Micro Air Vehicles and Design of a Payload Carrying Flapping Wing Micro Air Vehicles.” Naval Postgraduate School, Monterey, California, March 2006.https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjIyNWNmZWE2MjU1MDA1OWM

[7] K. Sarah Shigeoka, ”Velocity and Altitude Control of an Ornithopter Micro Aerial Vehicle”, University of Utah, Masters Thesis, 2007. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjFmMWM2OWU5OGFkMTE2OGU

[8] G. J. Berman,. and Z. Jane Wang. Energy-minimizing kinematics in hovering insect flight. J. Fluid Mech. vol. 582, pp. 153-168. Cambridge University Press, 2007. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjI5ODlmMTdkMzg1YjljN2E

[9] M. A. Bolender, ”Rigid Multi-Body Equations of Motion for Flapping Wing MAVs Using Kanes Equations”, U. S. Air Force Research Laboratory, AIAA, 2009. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjdjZmM2OGFhNDdhN2JmMWI

[10] Andrea Serrani, t Benjamin E. Keller, Michael A. Bolender, David B. Doman. ”Robust Control of a 3-DOF Flapping Wing Micro Air Vehicle.” AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario Canada, August 2010. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjdiZTk1OGI2YWNmMTk2MmI

[11] P. Daniel, ”Flapping Wing Design for a Dragonfly-Like Micro Air Vehicle”, Masters Thesis, Rochester Institute of Technology, New York, 2011. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjEwYjg2MDcwZDQ2YmVmMDY

[12] Haithem E. Taha, Muhammad R. Hajj, Ali H. Nayfeh. ”Flight dynamics and control of flapping-wing MAVs.”A review.Springer. Nonlinear Dyn. DOI 10.1007/s11071-012-0529-5, 2012. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjQyZmU0YWEwNjAxODViNWM

[13] Christopher T.Orlowski n, AnouckR.Girard. ”Dynamics, stability, and control analyses of flapping wing micro-air vehicles.” University of Michigan, Progress in Aerospace Sciences, March 2012. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OmZhMzViNmY1NDBkNTcxMQ

[14] J.V. Caetano, J. Verboom, C.C.de Visser. ”Near-Hover Flapping Wing MAV Aerodynamic Modelling - a linear model approach.” Delft University of Technology, The Netherlands, Portuguese Air Force Research Center, Air Force Academy, Sintra, Portugal, International Micro Air Vehicle Conference and Flight Competition, Toulouse, France, September 2013. https://docs.google.com/viewer?a=v&pid=sites&srcid=YXN1LmVkdXxtaWNoYWVsLXRob21wc29ufGd4OjE2OTllYjFiNjhmODk3ZDg

[15] M. Dickinson. ”How a fly flies.” TEDxCaltech,California, Filmed Jan 2013. http://www.ted.com/talks/michael_dickinson_how_a_fly_flies#t-103637