Control of Flapping-Wing Micro Air Vehicles

Drawings and manuscripts from antiquity reveal that humans have long dreamed of building machines that can fly using flapping wings. Although humans have been incredibly successful at building machines that fly, few of these aircraft fly using the modes most often observed in nature. Most natural flyers achieve flight through the use of flapping wings. One reason for the slow development of flapping-wing flight has been that the high aerodynamic efficiency of flapping wings that exists at the small scales found in nature disappears at the larger scales required for manned aircraft. Thus, practical applications for flapping-wing aircraft did not exist until the recent advancement of small-scale, unmanned air vehicle technology. The challenge of creating small, powered flapping-wing vehicles that perform some practical functions now appears to be within reach.

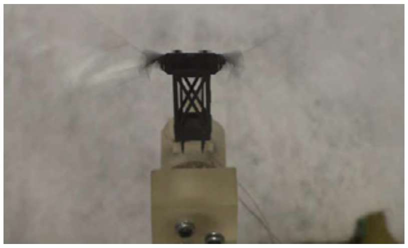
Numerous flapping-wing aircraft designers have been inspired by hummingbirds. (Photo by Bill Buchanan, U.S. Fish & Wildlife Service)

Beyond Conventional Flight Control

Most birds and many insects use periodic wing motion to propel themselves and maneuver. Most conventional flying machines are propelled by rotating machinery, achieve lift through rotating or fixed wings, and are controlled through the production of steady aerodynamic forces produced by rotors or movable wings. Many of the first powered flapping-wing micro air vehicles (MAVs) effectively replaced rotational propulsion modes with flapping wings and maintained control using conventional aerodynamic control surfaces or, in some cases, rotors. Recently, researchers have begun to develop aircraft that are controlled by manipulating the motion of the flapping wings themselves.

Control of a free-flying flapping-wing vehicle using only the flapping wings was achieved by the Aerovironment Hummingbird, a 19-gram aircraft that was powered by a DC motor and controlled by varying the angle of attack of each wing. Tiny piezoelectric flapping-wing aircraft in the 100-mg class have been produced by a research group at Harvard University; however, these aircraft have not yet achieved flight without being connected to an external power source. The interesting feature of control approaches that use only flapping wings is that the control forces and moments they produce are periodic rather than steady, as in a conventional aircraft. The periodic nature of the aerodynamics and the time scale separation between the vehicle flight dynamics and the wing oscillations allow the design of vehicles that can be controlled using a very small number of physical actuators.

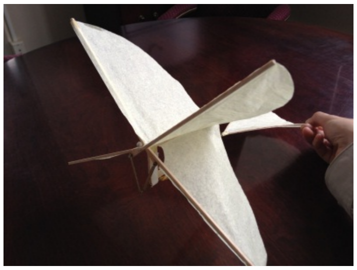
Conventional tail surfaces are used to control this flapping-wing MAV.



Two piezoelectric actuators enable independent control of the motions of the flapping wings on this test vehicle. (Photo by Maj. Michael Anderson, USAF)

Primitive Ornithopters

Ornithopters powered by rubber bands have been constructed since the 1800s. Although graceful and beautiful in flight, their practical value is limited. Many modern tail-controlled flapping-wing vehicles have borrowed elements from such designs. The four-wing ornithopter (right) propels itself by taking advantage of the interactions between the rigid leading edge and flexible trailing edges of the wings. The blowing action that occurs when the wings close and the suction produced when the wings open create an average horizontal component of force that propels the aircraft forward.



Balsa wood, tissue paper, wire, and rubber bands were used to create this ornithopter.

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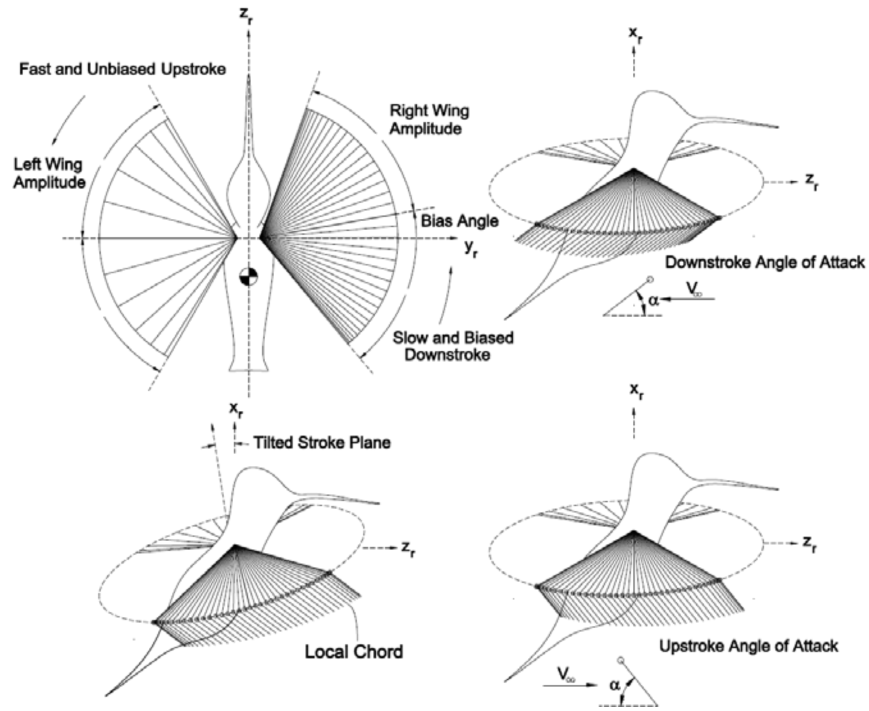
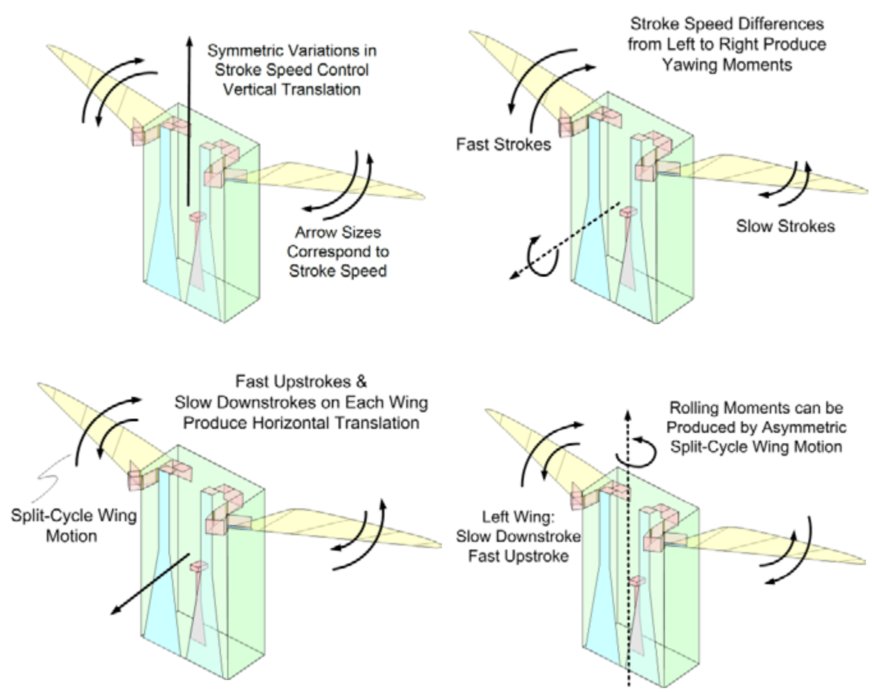
Exploiting Periodic Wing Motion for Control

Opportunities to explore control strategies for flapping-wing aircraft abound. Because the overall motion of the vehicle evolves on a much slower time scale than the motion of the individual wings, the vehicle motion is primarily influenced by time-averaged forces and moments. By manipulating a few variables that govern the periodic motion of two wings, the average forces and moments that are applied to the vehicle can be directly controlled. An exciting implication of this phenomenon is that the number of vehicle degrees of freedom that can be controlled can exceed the number of actuators that physically exist on the vehicle. Wing motion can be manipulated mechanically using numerous physical actuators or by using a single actuator whose motion is controlled by software. By shifting complexity from mechanical elements to software, the behavior of a small number of actuators can be governed by numerous virtual control variables that affect the time-averaged forces and moments applied to the vehicle. Some examples of wing motion parameters that may be used as virtual or physical control variables include wing stroke amplitude, wingbeat symmetric and asymmetric frequencies, wing stroke bias, angle of attack, and stroke-plane tilt angle. The strobed illustration to the right shows the effect of varying these parameters.

One method of controlling a flapping-wing aircraft is called split-cycle constant-period frequency modulation. This method works by using symmetric and asymmetric frequency as virtual control effectors, leaving the other previously mentioned variables fixed. The method allows the roll and yaw rotations and the horizontal and vertical translations to be directly controlled using two brushless DC motors or piezoelectric actuators that drive each wing independently. Differences in wingbeat period between the left and right wings produce a yawing moment. Collective changes in wingbeat period produce vertical accelerations. Differences between the upstroke and downstroke speeds that occur over each wingbeat period produce finite cycle-averaged drag forces that can be used for horizontal translation or the production of rolling moments.

Example Control Strategies





For more information: M.W. Oppenheimer, D.B. Doman, and D.O. Sigthorsson, Dynamics and control of a hovering biometric vehicle using biased wingbeat forcing functions, Journal of Guidance, Control, and Dynamics, 2011, pp. 204-217; D.B. Doman, M.W. Oppenheimer, and D.O. Sigthorsson, Dynamics and control of flapping wing micro air vehicles, Handbook of Unmanned Aerial Vehicles, Kimon P. Valavanis and George J. Vachtsvanos, eds., Springer, 2014 (to appear).