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Design, Development and Operational of an Ornithopter

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Abstract- **Biological flapping wing flyers achieve flight maneuverability and efficiency in low-speed flight environments that have been replicated by man-made flyers. FLAPPING BIRD design goals are to develop flyers that maintain flight in environments that biological flyers excel in which includes low speeds, hovering and urban settings. This flight is characterized by flow phenomena that are not well understood such as flow separation and vertical flow. The goal of this study is to perform a literature review about the aerodynamics of flapping flight and discuss the application to FLAPPING BIRD design. The study will evaluate the design initiatives of FLAPPING BIRD. Experimental and computational test method reviewed. Low Reynolds number aerodynamics are studied. The effects of aero foil aero elasticity and geometry are discussed. Then the applications of the aerodynamics to flapping motions are reviewed. Finally, operational FLAPPING BIRD designs are studied and recommendations are made to further advance the state of the art.**

I.INTRODUCTION

Flapping wing flight has numerous advantages over the conventional fixed-wing or rotor-wing flight. In many cases, birds can attain near-vertical take-off, perform agile dynamic maneuvers, and fly at rather slow speeds and uses environmental conditions via intelligent flapping, soaring and gliding in a highly energy-efficient manner. Imagine an aircraft that is ornithopter, are capable of carrying human occupants and may perform better than any hybrid system represented by similarly classes fixed-wing aircraft potentially integrated with helicopter rotor blades. In actuality, flapping-wing aircraft can perform on par with conventional fixed-wing aircraft. However, the added wing actuation enhances maneuverability and may achieve novel functionality (Buny et al., 2013)[1]. This includes hovering and flying with substantially lower energy requirements. There have been numerous attempts of building flapping-wing machines in the past (Bary et al., 2012; Books, 1953: Delaurier, 1993,1999,2005 Debel, 2007 hunt et al 2005, Kim, 2006,2009; Lin et al 2006: Mazaheri 2010. Regun et al. 2006) and while no fundamental obstacle exists in developing a hovering ornithopter capable of carrying a human, such aircraft have yet to be successfully designed and created. In contrast, simpler vehicles like helicopters and quadcopters can hover, maneuver, and carry large weights while there has not been a single cumple of large hind like robot hovering at site speed. Groups at MIT (Stunt Bird, 2011)[2] and Festo (Send et al, 2012 have recently built working examples of biologically inspired flapping bird-like bots. Festo's Smashing has a WInpan of 2 meters and weighs 450 grams. The wings passively bad to cart thrust ones during both the upstroke and downstroke. MIT's Phoenix can curry up to 400g of cargo und is mainly designed for controls research (Subharatri, 2009). However, these models still require some forward speed or appropriate headwind to fly. The same is true For all commercially available ornithopters and lying robots developed at other research labs (Jackowski, 2009) Successful hovering the speed was recently achieved with small hummingbird robotics, 2011) and a new generation of insect-like Micro Aerial Vehicles (MAV:) (Shyy et al. 1999). This class of flyers may have ale application in intelligence, surveillance, and reconnaissance missions (Back et al. 2011) Moreover, MAVS are also utilized to study the aerodynamics of biologically inspired flying (Partjupe 2012) With a focus on transportation and eventual goal to build a fully autonomous robotic flyer capable of carrying 100 kg, this paper reports on the development of a 20 kg, biologically inspired 2 ornithopter robot which was preceded by lighter 2kg prototype for proof of concept testing. The larger model is It can be utilized to study actuation mechanisms, various wing design, flapping strategies, and sensory-motor control. Our wing designs use some of the basic principles observed in nature. For example, a bird's wing is far more complex in its function than conventional an aircraft's wing During the down stroke, the feathers of many bird species stay together to form a smooth, solid surface whereas, during an upstroke, the feathers bend and spread to allow airflow between them (Biewener, 2011) Similarly, our designs explore air flux through the wings to reduce drag during the upstroke. Our advance flapping mechanism utilizes the Oie-To-Many (OTM) principle (Hunt et al, 2012. The second robot in this series that cannot fly on its own 2013) [3] where the motor never directly engages the wing during the lift generating stroke. Instead, the motor slowly builds up energy in the wing elastic element during the slow upstroke. The elastic element is teased from the motor, allowing for a fast down stroke. Hence, the power output can be multiple times larger than the power input. There is no need for the motor to passively hold the wing since the wing elastic element is already in a pre-tested condition while the wing is at its lowest angular displacement and supported by a whopper. Since the motor is damaged from the wing during the powerful downstroke, no unexpected motor damaging drag induced torques can be encountered. Furthermore, due to pre-known conditions (that is, in the same direction at torque and velocity optimum to its performance curves. Though machines may differ in form, the present approach is intended for the design of MAV in the order of scale as flying medium-sized birds, as schematically depicted in Figure 1. For the study, a baseline 15 cm semi span bi-wing configuration has been adopted, somewhat in the order of a dove. Figure 2. and Figure 3. Exhibit bio systems, in particular an eagle and a dragonfly, which will be mimicked in modeling the geometry of simple flapping baseline bi- and quad-wing ornithopter configuration, respectively. The geometries of both systems studied are depicted in Figure 2, bottom-right, for the bowing flapping ornithopter and Figure 3b for the quad wing ornithopter, with the size of a midsized bird. The sensory-motor control is crucial for ornithopter robot Manual flying of ordinary planes or helicopters is a non-trivial task. Manual flying of complex ornithopter with many degrees of freedom might be an impossible task, especially if main energy efficiency and/or maneuverability are required. The design team consisting of WPI students and professionals involved in this project envisions that a human operator may provide only never commands while the robotic system handles flight stability. Robotic commands should be based on rapidly changing sensory information including 12 variables global state vector per position and orientation spaces), internal state vector tie proprioception pressure. Wine spring constant and elongation) the motor may always rotate with temperature, wind, water concentration and localization of possible obstacles on the flyer's path.

II. ESSENTIAL PARTS OF AN ORNITHOPTER

A. Gear Box

In ornithopter, gear mechanisms are used in order to provide sufficient torque to flap the wings. A gear is a rotating machine part having cut teeth, which mesh with another toothed part in order to transmit torque. Two or more gears working in tandem are called a transmission and can produce a mechanical advantage through a gear ratio and thus may be considered a simple machine. Geared devices can change the speed, magnitude, and direction of a power source. The most common the situation is for a gear to mesh with another gear; however, a gear can also mesh a non-rotating toothed part, called a rack, thereby producing the translation instead of rotation.

B.Main Body

In general, the frame of the body of an ornithopter is made of Balsa Wood and Carbon. In order to minimize the weight of the ornithopter, Styrofoam is stuck in the gap of the body frame, maintaining appropriately sized gaps for placing microcontroller board, battery, receiver, and servos. A proper mount is attached in front of the body frame for the motor and gearbox.

C.Wing

For an ornithopter to be effective, it should be capable to flap its wings to generate enough power to get off the ground and travel through the air. The efficient flapping of the wing is characterized by pitching angles, lagging plunging displacements by approximately 90 degrees. Flapping wings increase drag and are not as efficient as propeller-powered aircraft. To increase efficiency of the ornithopter, more power is required on the down stroke than on the upstroke. If the wings of the ornithopter are not flexible and flapped at the same angle while moving up and down, the ornithopter will act like a huge board moving in two dimensions, not producing lift or thrust. The flexibility and movability of the wings enable their twist and bend to the reactions of the ornithopter while in flight.

D. Tail Wing

In order to steer an ornithopter efficiently and perform turns easily, the necessary condition is the stabilization of a free flight ornithopter, which depends on its tail. The tail of an ornithopter is generally a V-shaped tail with an angle of 120 degrees. It is made of Balsa Wood or Carbon and a Fiber or Plastic sheet is used to cover it. Two steppers or servos are mounted on the body frame to move the rudders attached to the tail, which are used to change the direction and pitch of the ornithopter.

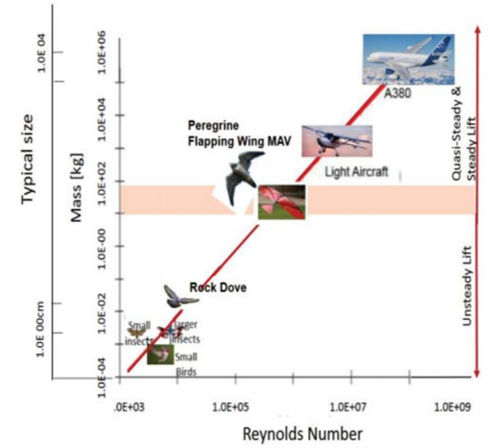


Figure 1: Reynolds number range of flying biosystems and vehicles.

III. AERODYNAMIC ASPECTS OF AN ORNITHOPTER

Lift is the force that utilizes the fluid continuity and Newton's Laws to create a force perpendicular to the flow of fluid. Lift is opposed by weight as it is the force that pulls things towards the ground. Thrust is the force that moves things through the air while drag is the aerodynamic force that reduces speed. The wings of the ornithopter are attached to the body at a slight angle, which is called the angle of attack; the downward stroke of the wing deflects air downward and backward, generating the lift and thrust. The surface of the wings is designed flexible which causes the wings to flex to the required angle of attack in order to produce the forces essential for achieving flight.[4]

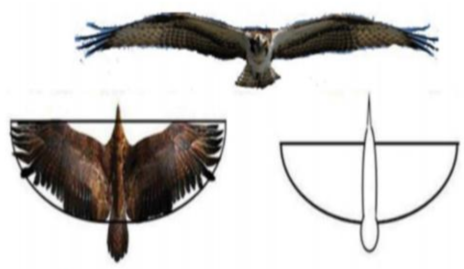


Figure 2: A generic semi-elliptical ornithopter wing planform adopted from eagle-wing planform. Top: Frontal view of an eagle; Left: Top view; Right: Baseline model.

IV. FLIGHT MECHANISM OF ORNITHOPTER

Ornithopter cannot take-off from the ground directly, this support is essential for this purpose. To fly an Ornithopter, its motion is triggered by providing its support through our hands. For initiating the motion, the power supply for motor and servos is switched on and then the whole dynamics of the ornithopter is controlled by the simulator. Directions or throttle is controlled appropriately for smooth and stable flight. Rudders kept in different ways to change the direction can be explained as follows: -

1. If both the rudders are in upward direction then the Ornithopter deflects in a downward direction.
2. If both the rudders are in a downward direction then the Ornithopter deflects in an upward direction.
3. If the rightward rudder is in an upward direction and the leftward rudder is in a downward direction then the ornithopter deflects in the leftward direction.
4. If the rightward rudder is in the downward direction and leftward rudder is in upward direction then the ornithopter deflects in the rightward direction.

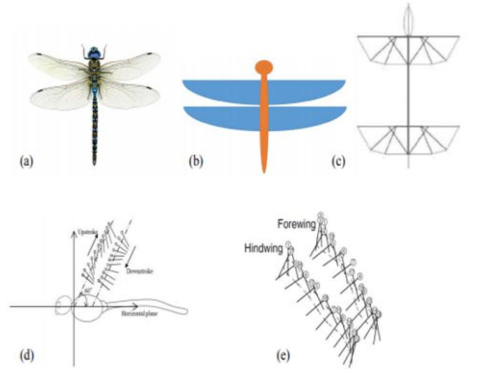
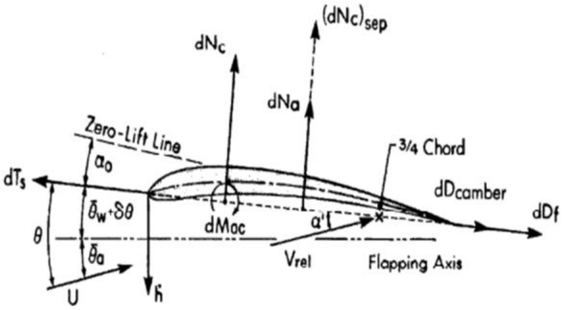


Figure 3: a) Dragon fly as a quad-wing ornithopter; b) A Computational model for a quad-wing ornithopter; c) Proposed experimental model for a quad-wing ornithopter; d,e) Upstroke and downstroke motion of a dragonfly [3].

V. CALCULATIONS



The illustrated figure describes the kinematics for each section of the wing. The wing's aspect ratio is assumed to be large enough that the flow over each section is essentially chord wise (in mean stream direction). Therefore, the section's circulatory normal force is given by

$$dNc = \frac{\rho UV}{2} Cn(y)cdy \qquad (1)$$

$$dNnc = \frac{\rho \pi c^2}{4} V_g dy \qquad (2)$$

V is the flow's relative velocity at ¼ - chord location, where

$$V_g = U\alpha - \frac{1}{4}c\theta \qquad (3)$$

Using these relationships, the relative velocity at three-quarter chord point which is used for the calculation of the aerodynamic forces can be established. The three quarter chord theorem was first derived [6] for the properties of the bound vortices on a wing of infinite aspect ratio. It states that, concentrating the lift at the quarter-chord line, the downwash produced by it at the three-quarter chord the line is the same as that produced by the flat-plate vortex distribution, equation (4), which is constant along the chord. The relative angle of attack at three-quarter chord, α, is then given by

$$\alpha = \frac{hcos(\theta - \theta_f) + \frac{3}{4}c\theta + U(\theta + \theta_\mu)}{U} \qquad (4)$$

Where $\alpha = Ae^{i\omega t}$

and α is a periodic function of time

Now,

The equations for the segment's instantaneous lift(L) and thrust(T) are given as

$$dL = dNcos\theta + dFxsin\theta \qquad (5)$$

$$dT = dFxcos\theta - dFxsin\theta \qquad (6)$$

Integrating along the span to get the whole wing's instantaneous lift and thrust:

$$L(t) = 2\int_0^2 cos\emptyset dl \qquad (7)$$

$$T(t) = 2\int_0^2 1dt \qquad (8)$$

Where $\emptyset(t)$is the section's dihedral angle at that instant in the flapping cycle. The wing's average lift and thrust are obtained by integrating $L(t)$and $T(t)$ over the cycle, that is performing integration with respect to cycle angle, $\emptyset$, instead of time, t, where

$$\emptyset = \omega t$$

So that average lift and thrust are expressed as

$$L = \frac{1}{2\pi}\int_0^{2\pi} L(\emptyset)d\emptyset \qquad (9)$$

$$T = \frac{1}{2\pi}\int_0^{2\pi} T(\emptyset)d\emptyset \qquad (10)$$

For separated flow, the expression for input power is given as

$$dP_{in} = dN_{sepa-fl}\,[hcos(\theta - \dot{\theta}) + \frac{1}{2}c\dot{\theta}] \qquad (11)$$

The instantaneous aerodynamic power absorbed by the whole wing is given by

$$P_{inst}(t) = 2\int_0^2 dP_{in} \qquad (12)$$

and the average input power, throughout the cycle, is given by

$$\dot{P}_{in} = \frac{1}{2\pi}\int_0^{2\pi} P_{in}(\emptyset)d\emptyset \qquad (13)$$

The average output power from wing is

$$\dot{P}_{out} = \dot{T}U$$

…(14)

The average propulsive efficiency can be estimated from

$$n_{\dot{avg}} = \frac{\dot{P}_{out}}{\dot{P}_{in}}$$

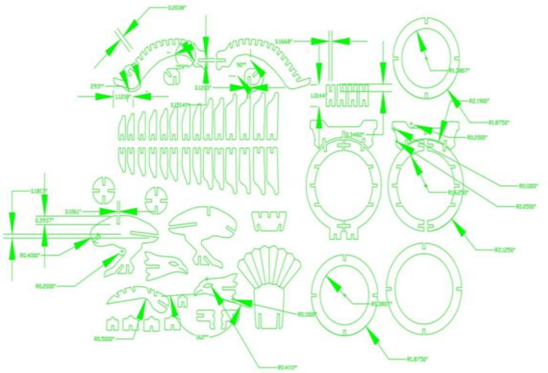


Figure5. The dimensions of eagle to prepare the prototype

VI. SMALL-SCALE PROTOTYPE DESIGN SUMMARY

Given the motor specification (24V, brushed electric motor), this model is able to attain 2.5Hz flapping frequency while results in negligible lift forces due to downward forces due to the wings and slider.

Moreover, the model suffers from added complexities due to insufficiencies in design. The use of a slider-crank drive mechanism provided many inherent disadvantages. One of the disadvantages of the crank drive mechanism included wing motion.[7] During the flight, the wings spent more time above horizontal rather than below it. Other disadvantages including wing rotation with non-constant angular speed due to the gear crank system when transforming upstroke movement into downstroke, movement and the transmission of forces at the worst transmission ratios, i.e. the crank would provide zero force the initial descent of the downstroke. For these reasons, data from the first experiment was insufficient and the available force plate was not sensitive enough to detect generated lift forces. As a result, new concepts were incorporated to build a second, larger model. This model would be more advanced in terms of design aspects and it would generate more pronounced lift forces that could then be experimentally studied. In addition to these problems during the experimentation, other technical issues also showed up. Namely, the acrylic platform broke, and it had to be fixed using bolts. Furthermore, due to inertial forces, wings bent while they were flapping and they had to be straightened after the experiment was over.[6]

Figure6. Prototype of Ornithopter made using acrylic glass

VII. MANUFACTURING

Two smaller gears for the large-scale prototype design were produced from one big gear using the CNC lathe machine. The big gear that was originally 3.40" in length and 2.00" in diameter was cut in half and processed to the final shape. Shafts for the device were cut from 0.5" diameter low carbon steel rod to the desired length of 4". Next, 0.5 in length end segments of the cut shafts were reduced in diameter to 7/16" using CNC lathe. After lathing, the shafts were threaded using a 7/16"-14 dyes. The structure of the machine was made from low carbon%" thick 2 or 3 in wide steel bars. These bars were reduced to their final shape using a CNC milling machine. Wing's bones were made out of carbon plates, these parts too were processed using CNC mill. The flappers were made from thick 2" wide low thick and manual taper. Once raw stock materials were machined, different parts were put together using either Tungsten Inert Gas (TIG) welding or Metal Inert Gas (MIG) welding machines. 3" by 3" aluminium plates and diameter rods using CNC mill, manual threaded, and manual taper. Once raw stock materials were machined, different parts were put together using either Tungsten Inert Gas (TIG) welding or Metal Inert Gas (MIG) welding machines. Wings were manufactured from 1/8" thick 1” by 0.5L-shaped aluminium rods and parachute nylon fabric. L-shaped aluminium rods were put together into the wing frame using TIG welder while nylon was attached to the wings using high-temperature hot glue gun and glue sticks.(Reference of using Figure 5) Once all the parts were manufactured, they were assembled together Bearings were press-fitted into plates and wing bones, and shafts were press-fitted through the inner bearing holes. Wing's bones were drilled and wings were attached to them using screws. Springs were placed on upper shafts and they were attached to the wing bones using chords. The motor was mounted on the aluminium plate, attached to the device via two 3/4" diameter standoff rods, and connected to the driving shaft via spider coupler.

Drive Mechanism

This wing drive mechanism is a version of the One-To-Many (OTM) principle. The motor never directly engages the wing during lift generating downstroke. The spring-based drive mechanism in the larger ornithopter required the use of two cantilevered driveshafts in between parallel plates. Slight misalignment between the plates caused either by manufacturing precision or by large force wing dynamics generated relative motion between the gears that engage wing bases.[8] From the experiments, the misalignment varied a lot. Three situations were encountered during the experiments: large friction between gears, and the wing gases, and gears barely touching each other and not engaging. This problem was solved by using gears that had relatively less and longer tech. New gear teeth did not slide past one another and they remain fully engaged during the experiment. The main advantage of the spring-based drive mechanism is that the motor never directly engages the wing during the lift generating downstroke Instead, the motor slowly builds up energy in a wing elastic element during the slow upstroke. Hence, the power output can be multiple times larger than the power input. Similarly, there is no need for the motor to passively hold the wing since the wing elastic element is already in pre-tensed condition while the wing is at its lowest angular displacement and supported by a stopper. Since the motor is disengaged from the wing during the powerful downstroke, no unexpected (motor damaging) drag induced torque may be encountered. Finally, due to pre-known conditions (that is, wing spring constant and elongation), the motor may always rotate in the same direction at torque and velocity optimum to its performance curves.

VIII. SIMULATION

A detailed numerical dynamic simulator based on the heavy-weight (M=20 kg, L=I. 22m, W=0.78m) model was developed. It includes the masses, center of mass locations, and moments of inertia of all parts treated as rigid bodies (deformations due to motion were neglected, K1=1470Nm) and constant tether spring (K2=300N/m). The wing equation of motion during the downstroke includes drag forces with quadratic dependence on velocity, spring forces, and inertia terms. The entire "bird" equation of motion includes the weight, spring force, and lift force as a component of drag force and inertia terms. In this tethered condition, it takes approximately 50 milliseconds for charged spring to return to its original shape. Displacement of the center of mass of the body of the whole bird at this time is 1.2 cms above its resting state After 250 milliseconds, the center of the mass of bird rises about 7 cms. The hovering single flap, steady-state solutions for a scaled-up untethered model with m=100 kg, L=3m, W=2m, and same opening wing angle were evaluated. Both the wing spring constant (K1) and time (t) when the downstroke is triggered after the apex zero vertical velocity) were optimized to best match position and velocity cyclic conditions within the parameter space of interest. Various steady solutions exist and an average hovering power of less than 5.6kW (t=0.02s, K1=11kN/m, leading to f=8.6Hz flapping frequency) per wing can be achieved. The simulation takes into account both strokes as well as non-zero vertical velocity during a single steady cycle. Finally, the addition of non-zero forward speed makes these power requirements substantially small.

IX. CONCLUSIONS

Although no fundamental obstacle exists for developing a human carrying ornithopter robot capable of hovering solely by flapping wings, none have been successfully built. This project tried to solve this issue by pioneering the stops for building such a device, and by proving that ornithopters are more advantageous over fixed-wing and rotary blade aircraft through experimentation. To validate the claim, an analytical study, power analysis, and physical experiments were conducted towards the realization of an ornithopter robot capable of hovering and generating a 100 kg lift force. Then the results from the theoretical study were scaled down and experimentally tested. The analytical study and power analysis indicated that for a human carrying ornithopter, an average hovering power of 56kW is achievable via a flapping wing mechanism which is less than the 112 kW needed for an equivalent fixed-wing aircraft. Two prototypes were constructed to validate the theoretical model of flapping flight and both models utilized two different actuation and control mechanisms.

Multiple experiments were performed under repeatable lab conditions. The experiment with the final design was successful and it validated the proposed aerodynamic a numerical model with reasonable accuracy, Ornithopters have many innate advantages over fixed-wing and rotary blade aircraft. Due to their high maneuverability, large range of possible speeds, and reduced power requirements, ornithopters may be a viable and attractive mean of intelligent Transportation that deserves more dedicated research and practical realization.

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