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Description of the Pajaro ornithopter
And analysis of its efficiency

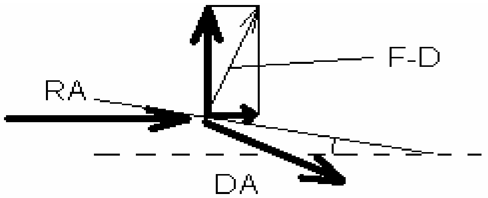
Introduction

The Pajaro ornithopter is an airplane that uses four flapping wings for propulsion and lift and a compressed air engine from an Air Hogs® airplane. The Pajaro is made of balsa wood, plastic, sophisti wrap (similar to Mylar® but transparent) and some metal components in order to keep the design light enough. The idea of making an ornithopter started after three failed attempts of making a smaller model last year.

How does it work?

Consider a flat plate inclined at 15 degrees to the horizontal. If the plate is moved forward through the air in the horizontal, the plate produces lift at 90 degrees to the horizontal and a small amount of drag. The motion of the plate produces a relative airflow that is always opposite to the motion of the plate. The addition of this two vectors yields a vector that is in most cases less than 90 degrees to the horizontal (Fig 1). This vector is a force vector and it is equal to the difference between the force vector produced by the relative airflow and the deflected airflow. In theory, there is no change in the magnitude of this vectors and the lift-drag vector is produced only because the flat plate deflects the relative airflow in a different direction (Fig 2), (Fig 3).

(Fig 1) Direction of motion

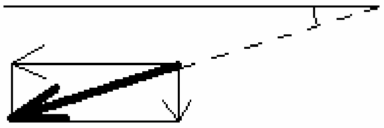


(Fig 2) Resolution of the lift-drag vector

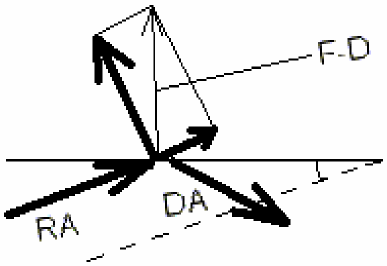
(Fig 3) Relative airflow force vector – deflected airflow force vector = lift-drag vector

Oscillating flat plate

Now consider a horizontal plat plate that is moving up and down and moving forwards. For the following explanation we only need to consider the plate moving down since the up going motion can be considered as an up going motion observed from the top. The sum of the velocity vectors in this case equals a velocity vector with a direction that is between 0 and 90 degrees below the flat plate (Fig 4). Since the relative airflow acts in the opposite direction, we have the same effect as if the plate was traveling forwards with an angle to the horizontal as in (Fig 1), producing the same lift-drag vector. From the point of reference of the plate, the two situations can be identical (Fig 5).

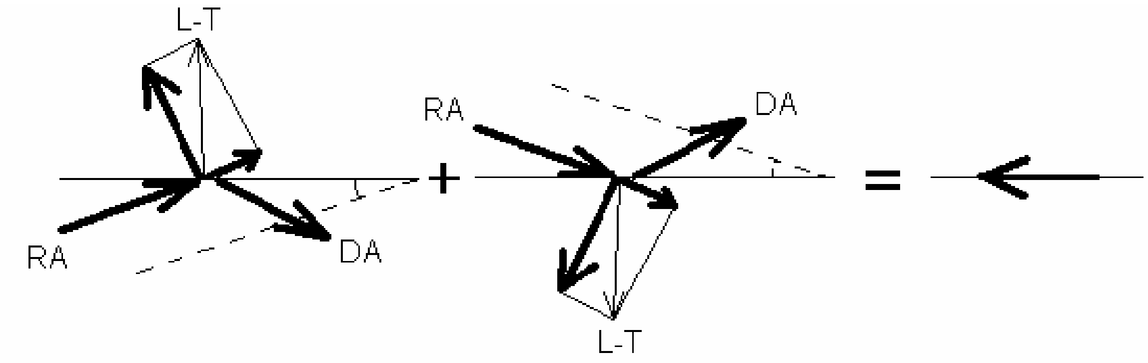


(Fig 4) Resolution of velocity vector



(Fig 5) Relative airflow and lift-drag vector

The only difference between Fig 2 and Fig 5 is that the orientation of the wing with respect to the fuselage is different. From the point of reference of the fuselage (body of the aircraft) that is parallel to the horizontal in Fig 2, the wing is producing lift and drag, but in Fig 5, the fuselage is parallel to the plate and the lift-drag vector becomes a lift-trust vector because it is tilted forwards with respect to the fuselage. Nevertheless, since we are talking about oscillating motion, the lift vectors actually cancel out leaving only the trust vectors (Fig 6). There are ways of making the up going force vectors smaller so that there is also a net lift vector and they will be discussed later.

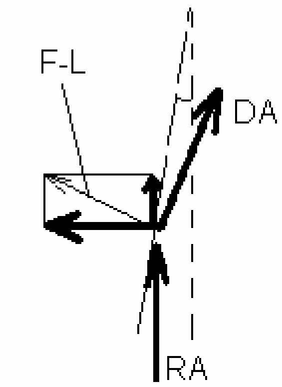


(Fig 6) Down going force vectors + up going force vectors = net forward force vector

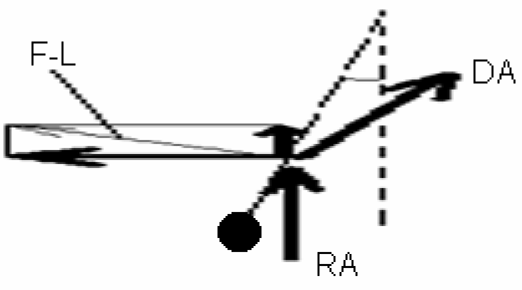
Therefore, an oscillating flat plate generates trust if it moves forward. However, how does it start moving?

The plunging oscillating flat plate model

Again for the following explanation we only need to consider the plate moving down since the up going motion can be considered as an up going motion observed from the top. Consider Fig 2 again, but in this case rotated counter-clockwise 90 degrees (Fig 7).

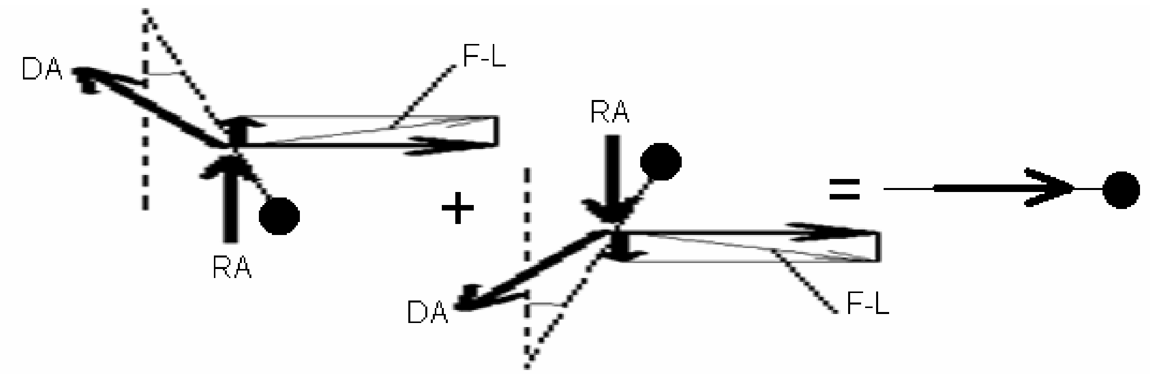


(Fig 7)



(Fig 8) Down going plate plunging up moving about front axis (black circle)

Now the wing is moving down with respect to the fuselage and it is producing lift and trust without moving forward. If the wing is designed so that it plunges up and down to a certain angle about a front axis using the force of the relative airflow, the same effect will happen when the wing is moving up, with the sum of all the vectors in the up and down going motions again producing a net forward force (Fig 9).



(Fig 9) Down going force vectors + up going force vectors = net forward force vector

NOTE: The way the wing generates lift is by tilting the whole wing and fuselage assembly slightly upwards, using aerodynamic forces produced by the craft's tail assembly, and therefore using a small vector component of the trust to produce lift.

Conclusion

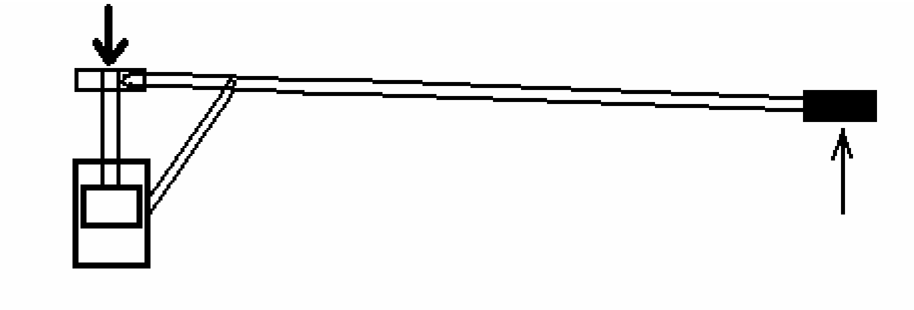
Both models, the oscillating flat plate and plunging oscillating flat plate, are working together to produce trust. At first the plunging of the plates, or wings, produces the trust, and when a certain speed is reached both models play a part in producing trust. The two models are related by the plunging angle and the speed of the flapping (up and down motion) of the wings since those factors affect the direction of the relative airflow and therefore the direction of the lift-trust vector.

First Designs

Our first design was based entirely on a small AeroDavinci® ornithopter and was powered by a rubber band. The problem with scaling a rubber-powered airplane is that rubber bands come in small sizes, and the tension in the rubber band generates even more friction because the axle that moves the wings is connected to it. The axle has a bend at the end of it and there is enough tension in the axle to make the bend dig into the balsa wood, increasing the friction by a factor much greater than the scaling factor. After many improvements, like using three rubber bands instead of one, and using plastic around the bend in the axle, we were able to fly this ornithopter for two or three seconds at a time.

The second design had more problems than the first design and was eventuality dismantled for parts. The main problem is that the wing did not flap. This was not a lack of power or endurance since we installed the compressed air engine and the tank from an Air Hogs® airplane, it was the ornithopter itself that had problems. We tried to install an engine in an arrangement that was made to use a rubber band and the problem is that the length of the different parts could not fit in order to make the engine work.

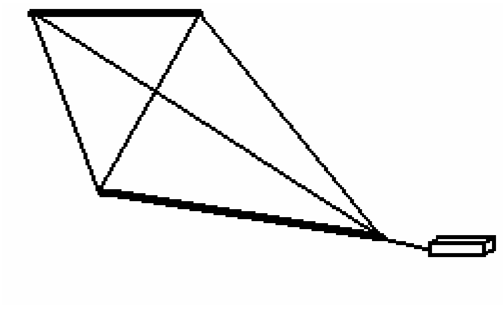
Our final design, Pajaro, was made so that the engine piston could move without friction and with space to spare. But it was not working either and it looked like the same problem we had with our second prototype. After a few hours of observation we found that the problem had to do with we wings; they were not heavy enough. We did not want to add any extra weight but we preferred a working prototype instead of one that does not work. The problem is that when the piston changes direction, it does not have enough force to open the valves in the engine and the inertia of the weight in the wings gives the piston enough force, when it is changing direction, to open the valves (Fig 10).



(Fig 10) Engine, front of wing, and weight assembly

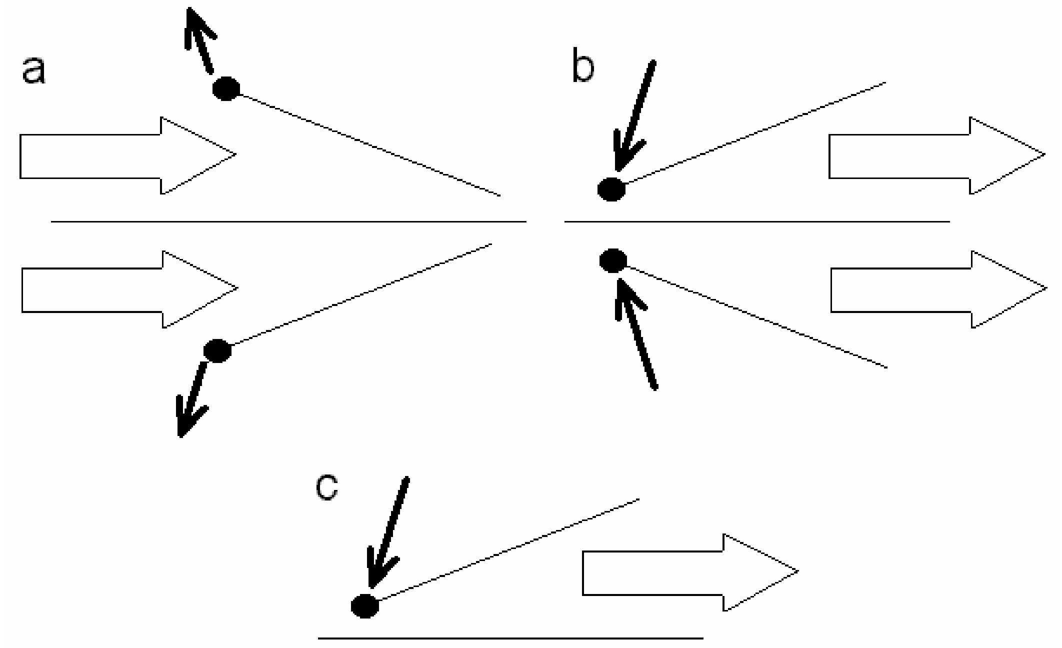
New Features

The Pajaro ornithopter features an all movable tail assembly that is constructed of 6 balsa sticks forming a light and strong structure composed of triangles (Fig 11).



(Fig 11)

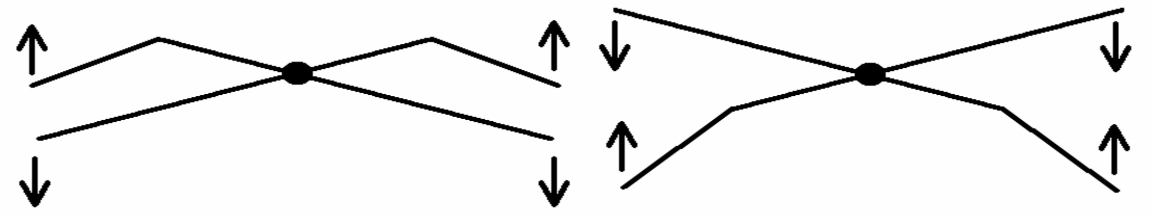
The wings do not have a covering near the center section since as you get closer to the fuselage, the speed of the up and down going motion of the wing section at that same location becomes zero. Four wings where used because each wing works more efficiently, moving in counter-phase, because it is the same as if each wing were in ground effect, displacing more air than the four wings alone (Fig 12). The theoretical models in the beginning of this report are not detailed enough to explain the increase in trust when this arrangement is used.



(Fig 12) a) Air comes towards the wings, b) air is displaced out; notice line of symmetry, c) wing in ground effect.

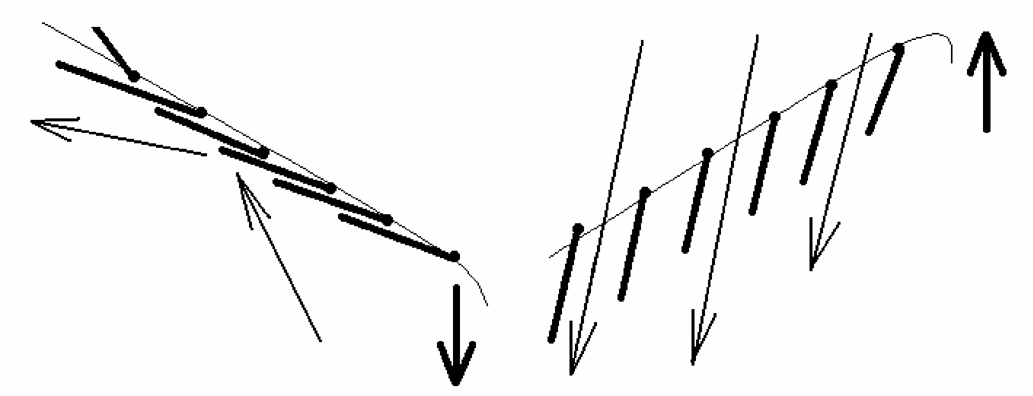
Future Improvements

In the first section, it was mentioned that it was possible to produce lift directly from the flapping. We found two ways of doing this: one is by making the wings bend longitudinally only on the up going motion, decreasing the force caused by the relative airflow, therefore decreasing the vector component that opposes the lift component in the down going motion (Fig 13). This is how birds increase their flapping efficiency.



(Fig 13) Front view of ornithopter in flight with bending wings

The other method to produce lift directly from flapping is by having small flaps in the whole wing surface that only open when the wing is going up, again decreasing the force caused by the relative airflow, therefore decreasing the vector component that opposes the lift component in the up going motion (Fig 14).



(Fig 14) **Down going wing** **Up Going Wing**

Resources:

People:

- Professor De Laurier. E-mail: jdd@utias.utoronto.ca

Websites:

- Flap Design. http://www.ornithopter.org/flapdesign1.shtml
- BBC Science Shack. http://www.open2.net/scienceshack/flying_make_pg1.htm
- Flapping Flight. http://www.ornithopter.org/flapflight/birdsfly/birdsfly.html
- Flapping Flight (different site). http://www.nurseminerva.co.uk/adapt/flapping.htm
- Bird Slow Flapping Diagram. http://www.paulnoll.com/Oregon/Birds/flight-slow-flapping-diagram.html
- Biomimetic Flight. http://www.personal.psu.edu/faculty/l/n/lnl/097/anders/index.htm