TETRA-PTERA – EMPIRICAL AND EXPERIMENTAL INVESTIGATION OF A STUDENT DESIGNED AND FLOWN FLAPPING WING MAV

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Abstract

Tetra Ptera is a student project carried out at the Faculty of Aerospace Engineering at the Technion - Israel Institute of Technology. This document summarizes 10 months of work from November 2008 until July 2009.

Tetra Ptera is a flapping winged MAV designed to fly indoors at low speeds carrying a camera as a payload. After a thorough market survey was performed, it became apparent that although there are several flying models of flapping winged MAVs, there is no fully based analytical analysis of the flapping wings aerodynamics. As a result, a traditional primary design of the aircraft was difficult to achieve. Therefore, experimental methods were implemented in order to analyze the different parameters and aspects of the wing's behavior and thrust.

During the two month experimental period, a preliminary model was built, as a result of a modular building plan we established. Eventually the final model was built and flown, according to the optimized parameters found during the experiments.

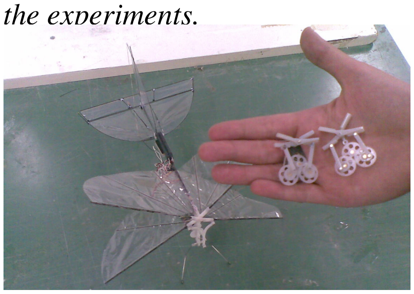

Fig. 1. Tetra Ptera

1 General Introduction

MAVs (micro air vehicles) have become a very popular theme in aviation, mostly due to the increasing need for small, low speed, highly maneuverable hovering aircraft. Insects, which inhabited the Earth for over 35 million years, have highly developed maneuverability and hovering capabilities, and therefore it is logical to try and copy their movements in order to achieve hovering and flapping wing capabilities. However, flapping wing aerodynamics, which is characterized by small Reynolds numbers, is an unsolved subject, in spite of extensive research. So all we have left to do is to turn to nature and try to imitate it.

The subject of flapping winged MAV gathered momentum in the mid 90's, thanks to the enormous development in cellular communications, which was characterized by the minimization of components like batteries, motors, cameras and more.

Another event that had an effect on flapping MAVs is the official specification defined by DARPA in 1997, which classify a MAV as:

1. Wingspan – up to 15 cm.
2. Weight – up to 100 grams.

1.1 Project Goals and Requirements

The main goal was to design, examine and build a flapping winged MAV capable of carrying a camera. The project requirements were:

- Wingspan: 15-30 cm.
- Weight: 16-20 grams (including payload).
- Flight time: 5 minutes.
- Non autonomous flight – remote control capability.

2 Market Survey

After defining our goals, a market survey was made, to examine different solutions and methods to implement a MAV which uses its wings to flap. The most suitable MAV found are summarized in the following table:

Name	Origin	Wing configuration	Propulsion	Weight [gr]	Wingspan [cm]	Flight time [min]	Notes
Delfly II	Delft Univ.	X-Wing	2 Lithium batteries, brushless DC motor	15	25	15 – straight flight 8 - hover	Camera as a payload, Transverse shaft flapping mechanism
Microbat (4th model)	UCLA + Aero Vironment	V-Wing	2 Lithium batteries, coreless motor	14	22.9	~25 (no hover capabilities)	No payload, Staggered crank flapping mechanism
Mentor	SRI + Toronto Univ.	X-Wing		550	30	15 - hover	exceeds DARPA's definitions for MAV
NPS	Naval Post Graduate School (NPS)	2 front – fixed. 2 rear - flap	1 lithium battery, brushed DC motor	13.4	27	>3	Different concept: front wings are fixed, and the rear wings flap – improves the dynamic stability.
Entomopter	Prof Robert Michelson + Georgia Univ.	X-Wing (2 front and 2 rear wings, flapping in an inverted phase)	Chemical energy - RCM	50	15		RCM can also produce differential lift for roll corrections (through small airflows on the wing) and a small amount of electricity.

Table 1: Market Survey

3 Aerodynamics

In the past, aerodynamic analysis of a flapping wing was always performed through steady state analysis, similar to the thin airfoil theory. This kind of analysis will result in a wing that produces only 35%-50% of the body mass it is lifting. This is contradictory to the millions of birds, bats and insects found in nature who have been flying for millions of years! Therefore small winged body aerodynamics is different, and there are unsteady phenomena which increase the produced lift significantly. This phenomena is characterized by low Reynolds numbers (10-100,000) and leading edge vortices creation, which increase the turbulences dependent lift and delay the airflow interruptions on the wing and therefore prevent the wing's stall. These are only recently discovered phenomena so there is a lack of a well–based analytical analysis of flapping wings aerodynamics.

This is why we should continue to explore nature as a major source of knowledge and as a role model.

3.1 Difficulties and Approaches

Flying insects operate over a broad range of Reynolds numbers from approximately 10 to 100000 (determined primarily by their variation in size). Although at high Reynolds numbers the viscous term in the flow equations is negligible, at low Reynolds numbers the viscosity cannot be neglected. It is still smaller than inertial forces, but still it affects the flow structure and cannot be ignored. Although the effect viscosity has on the flow field is different for low or higher Reynolds numbers, in both cases this effect can not be analyzed analytically, because the flow field equations can be solved more than one way. Obviously exact initial conditions can help narrow the possible solutions but still there will be more than one solution.

There are many approaches to solving the complex subject of the flapping wing airflow field, but we cannot clarify each and every one of them in this article (see Refs. [1]–[9]). One can say that none of this is fully proved analytically, moreover, each approach assumes its own assumptions and theories, which also questions the correctness of these assumptions.

3.2 Aerodynamic phenomena

In addition to the different approaches for solving the flow field around a flapping wing, there are several non-steady aerodynamic phenomena related to the creation of additional lift by the wing. Among these phenomena is the "Wagner effect" which actually causes a reduction of the lift produced by the flapping wing. This effect is related to a vortex created near the trailing edge of the flapping wing, which is turning in the opposite direction to the circulation created around the wing. Therefore it reduces the circulation causing the created lift to become smaller.

Another phenomenon is the "Clap & Fling effect", also known as "Weis-Fogh mechanism". This low Reynolds related phenomenon, describes the encounter between two "flat" wings (near180^0 flapping angle) every half a flapping cycle. This encounter (see Fig. 13) involves a slanted approach of both wings until their leading edges meet. Then the wings start to turn around their leading edges until they meet ("clap"). Later on the wings begin to move apart from each other while turning around their trailing edges ("fling") and the low pressure between them causes an induced speed into the area formed between the wings, which forms powerful vortices around the wings. These vortices are equal but in opposite directions, causing an increase of the lift on each wing individually, but keeping the total amount of circulation around the wings at 0. Apparently this phenomenon does not exist in nature in its full implementation, because it wears out the wings of the insect, but it does exist in partial implementations, and still insures a bigger lift than expected.

There are several other phenomena such as Leading Edge Vortices (which moves down the wing, delay its stall and increases the lift), "Cramer Effect" (using vortices created around the wing in the rotation between the flap phases to increase the lift). There are many more, all of them explain how the unsteady aerodynamics used in the flapping motion produces larger lift then expected.

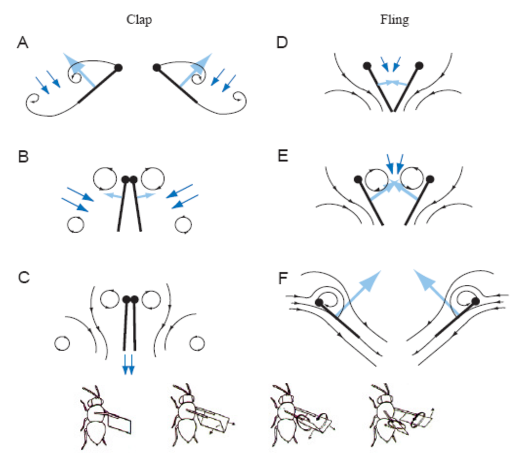

Fig. 2. "Clap & Fling" affect - process scheme.

Comparison to Nature

Is it legitimate to compare small insects to an artificial larger flapping winged MAV?

To answer that, let us first define a few flapping flight parameters:

- R – one wing length
- n – wing flapping frequency
- m – insect\air vehicle total mass
- W – insect\air vehicle total weight
- Φ - flapping amplitude (maximal wing angle)
- S – both wings area
- WL – wing load ($WL = \frac{W}{S}$)

These parameter values vary drastically even between insects, but some important relations are kept in nature independently.

For example if we examine the wing loading parameter we find a relation between the gravitational and inertial powers and aerodynamic powers. If we explore each of them we discover that aerodynamic power relates to length in square, while gravitational power relates to length in the third power. Therefore the following connection is accepted:

$$\frac{W}{S} \propto \frac{l^3}{l^2} \propto l \propto W^{1/3} \tag{1}$$

Hence we have found a relation between the wing load parameter and the total weight. And indeed, data collected through decades, on airplanes, birds, insects and bats shows this relation indeed exists, as shown on Figs. 4 and 5.

The line in Fig. 4, and the star line in Fig. 5 represents the theoretical equation, and one can see that the behavior matches the theory with satisfying accuracy. You can see that even species that are rather far from the theory line are parallel to it. Therefore, a comparison between artificial air vehicles and insects is indeed legitimate.

Another parameter we can obtain from nature is the wanted wing length per a certain amount of mass we need to carry (see Fig. 3).

With this graph of wing length vs. weight we can estimate our required wing length. For example to carry 10-20grams, according to the graph a wing length of approximately 10cm, meaning a wingspan of 20cm is needed. This is called the rule of scaling and it is used to focus the dimensions of the pre-built vehicle in the primary design phase. These collected parameters are a good example of how nature can help us design and build a flapping winged MAV with an exact analysis.

Wing Design

The following parameters shall be used to design the wing: R, m, Φ, n.

Φ in a four winged MAV means the maximal amplitude between two wings (from the same side of the body). As mentioned, in this kind of wing configuration there is a major contribution by the "clap and fling effect" on the total thrust production.

The artificial flapping vehicle may be compared to a mechanism flying itself via air it "pushes" through its wings, like a propeller. This is why the aerodynamic forces and power the air vehicle produces or consumes can be analyzed through the rotor momentum theory. The analysis will be carried out for a hovering vehicle. It is important to note that a vehicle produces the most thrust while in a hover, because the thrust is only from the flapping wings and not partially due to lift produced from airflow on the wings. From the analysis via the rotor's momentum theory the following relations can be concluded:

$$m \propto SU^2C_L = \frac{(2R)^2}{AR} \cdot (2\Phi nR)^2 C_L \propto \frac{\Phi^2 n^2 R^4 C_L}{AR} \tag{2}$$

You can see the relation between the supported mass and the flapping parameters.

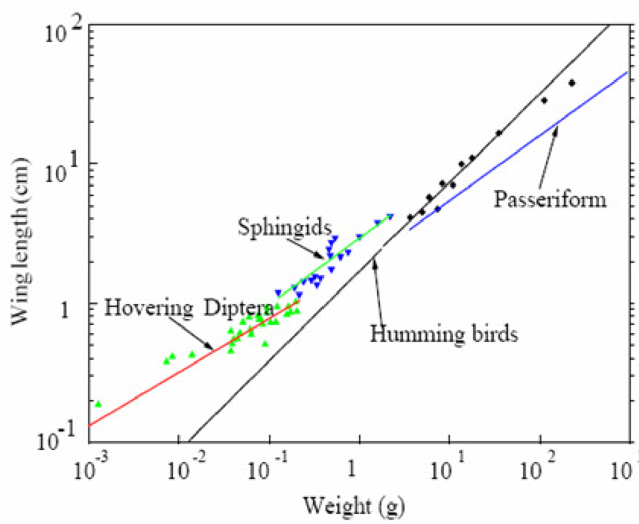

Fig. 3. Wing Length Vs Weight

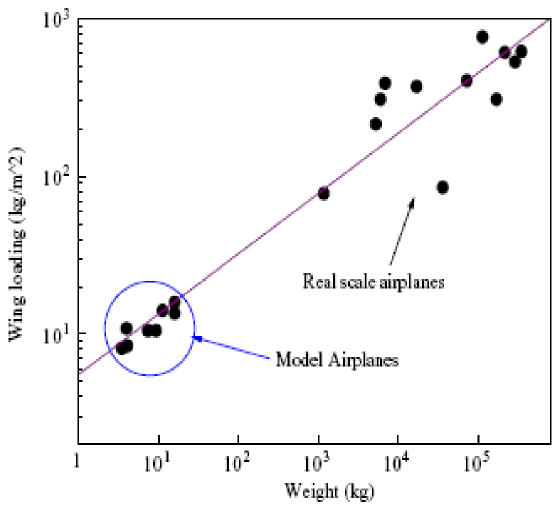

Fig. 4. Wing Loading Vs. Weight (Airplanes)

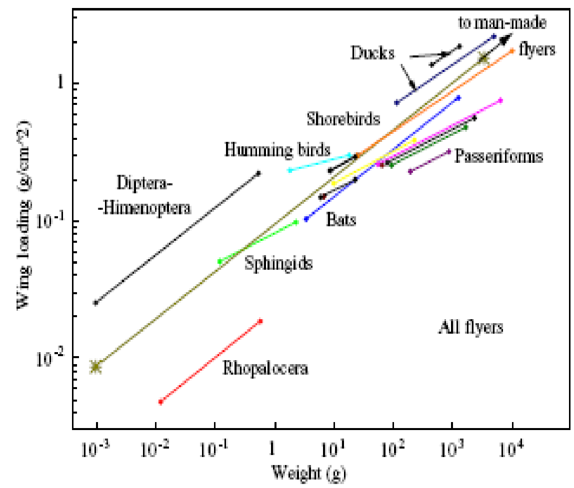

Fig. 5 Wing Loading Vs. Weight (Nature)

By setting typical values of gravity and air density, and a typical assumption for insects of a wing center of area in 0.5R, the lift equation introduced is (Ellington, 1999):

$$m = 0.387\frac{\Phi^2 n^2 R^4 C_L}{AR}. \qquad (3)$$

If the supported mass is known, and the lift coefficient is set as typical value (2-3 for insects) a relation between flapping parameters can be found. Later on this empirical relation is tested in the experimental phase, so the proportion factor we receive there will compensate for the error that might have been made by the lift coefficient assumption. Another parameter obtained through the rotor momentum theory is the induced power (assumed to be 15% more than steady state power):

$$P^*_{ind} = \frac{P_{ind}}{m} = \frac{(T)^{3/2}}{\sqrt{2\rho A}}\cdot\frac{1}{m}$$

$$T = mg, A = \Phi R^2$$

$$\Rightarrow P^*_{ind} = \frac{\sqrt{m\cdot g}^{3/2}}{\sqrt{2\rho\Phi R^2}}$$

$$P^*_{ind} = 1.15P^*_{ind} = 14nR\left(\frac{\Phi C_L}{AR}\right)^{1/2}$$

(4)

The first equation comes from the rotor hover power equation. The friction power consumed can also be calculated and the outcome will be:

$$P^*_{pro} = 18.2\Phi nR\frac{C_{D,pro}}{C_L}. \qquad (5)$$

Charles Ellington's theory was the main theory tested and validated in our experiments phase, and one of our major results was a correction factor to this theory, adjusting the equations to our own flapping winged MAV (see the experiments section).

In addition in order to optimize the design process, user-friendly simulation software was built, receiving known design parameters which can simulate other parameters, such as lift, wing size and different powers.

4 Experimental Analysis

During the experiments we tested the influence of the different flapping configuration parameters on the thrust and power consuming performance.

The experiment was performed in 3 stages: In the first stage, we tested the wing's configuration influence on the thrust and power consumption.

In the second stage the influence of the wing's area and aspect ratio was tested, on the chosen configuration from stage one of the experiments.

In the third stage the flapping amplitude was tested, for a wing whose configuration and dimensions are set from the first and second stages of the experiments.

Eventually we compared all the results to the theory, and combined it into a useful tool for an initial estimation of a wing's shape, dimensions and flapping configuration for an estimated wanted thrust.

Objectives

1. Optimization of the flapping configuration, as a function of the following parameters:
   a. Wing's configuration
   b. Maximal flapping amplitude
   c. Flapping frequency
   d. Aspect ratio
   e. Wing span
2. Obtaining graphs of Thrust vs. Flapping frequency.
3. Obtaining graphs of Thrust vs. Power
4. Comparison and validation of previous research.

Experiment program

As mentioned, three experimental stages were planned in order to optimize the wing's parameters:

1. Optimal wing configuration, out of three wing configurations: standard, extra, shifted
2. Optimal wing area and aspect ratio:
   - Wing configuration is the optimal one from stage one of the experiment
   - Part A of this stage is an experiment for wings with a constant area, but varying aspect ratio (or wingspan)
   - Part B of this stage is an experiment for wings with a constant aspect ratio but a varying area (or wingspan)
3. Optimal flapping amplitude
   - The optimal wing dimensions are tested for three different amplitudes

Test model

The test model was built in order to provide the right conditions for the wing's thrust tests. The desirable test output was the thrust as a function of the wing's flapping frequency, for several wing configurations.

In order to provide the tests' needs, the flapping mechanism had to be versatile.

Therefore, the main considerations in the building phase were:

- **Fast and simple wing replacement** – in order to maximize the amount of experiments per day. The model was changed several times in order to optimize this feature.
- **Flapping frequency change** – a simple interface was needed between the power source and the mechanism.
- **Amplitude changes –** was possible through different placements of the connecting rod to the leading edge.

Model development

As mentioned, the test model has undergone several changes in order to maximize its wanted characteristics. The first model was built with fixed wing roots that were glued to the main flapping joint. As seen in the figure, this model does not provide an easy way to change the wing, but it has several pins that provide different leading edge connection points for the connecting rods. Each point enables different amplitudes, which in this model are: 48°, 55°, 68°, 86°, and 112°.

In order to provide it with an easy wing-change mechanism, a new joint was made by a laser 3D printer. The new printed joint provided easy and fast wing change possibilities, accurate and coordinated wing connections, and general mechanism versatility. The new wing change process was carried out by inserting the leading edge rods into the matching holes in the main joint. The amplitude change process was carried out by placing the connecting rods upper axis pin through one of the pre-designed holes on the new printed joint. Each hole provides different amplitudes.

The new joint was indeed versatile enough for the model's needs, but a problem was discovered during its flapping capabilities tests. While flapping at high flapping frequencies (14 HZ and higher) the model created strong vibrations, apparently because of a dynamic imbalance due to the joint activity. The reason was the joint's longitudinal asymmetry. It is clear that the joint's lower "arms" are longer than its upper ones. Therefore the mass distribution is not symmetrical, and this caused inertial vibrations.

To fix this problem a new symmetrical joint was printed on the 3D laser-printer, which indeed withstood the high flapping frequencies (more than 20 HZ).

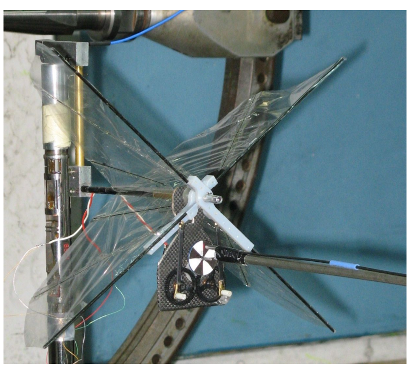

Fig. 9. Test model during a test run

Another area of development in the test model was the motor improvement. Even after the mechanism was fixed the model had problems reaching frequencies higher than 20 HZ in the full amplitude mode, mainly because the engine over-heated.

This problem was fixed by changing the motor to a more powerful motor, and changing the cog-wheel ratio in order to be closer to the engine work point (the first cog-wheel ratio was 30.72, which was gradually reduced to 18.07).

Experimental system

The measured parameters in our experiment are:
1. Thrust
2. Flapping frequency
3. Voltage
4. Current

The most challenging measurement is thrust, because of the fact that the forces produced by our micro UAV are only a few grams. In addition, the UAV body vibrates at frequencies that might cause a resonance of our measurement facilities. Therefore we need a measurement tool which is rigid and has a high frequency eigenvalue, so our flapping frequency will be much lower and will not influence the measurements.

Our optional measurement tools were:
1. 3 DOF (degrees of freedom) balance, with a kilogram scale
2. 6 DOF balance, with a 10 kg scale

An experiment was carried out to test each measurement tool for, force sensitivity, natural frequency (frequency eigenvalue) and measurement repeatability. All tested parameters have shown that the 6 DOF balance is better, with even special advantages such as easy interface and data collection. Thus, the 6 DOF balance was chosen to conduct the experiments.

The following scheme presents the experiment system:

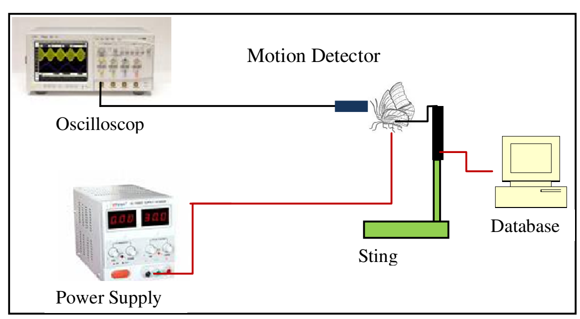

Fig. 10. Experimental system

The experiments were carried out in the low speed wind tunnel in the Technion's Faculty of Aerospace Engineering.

The balance is a 10 kg scaled balance, and it was placed in the wind tunnel. The wind tunnel itself was not activated (and was even blocked to prevent wind flow on the micro UAV), but its computer was the data processor of the experiment.

The following figure presents the connection method of the micro UAV to the balance, through a connector, built especially for the experiments.

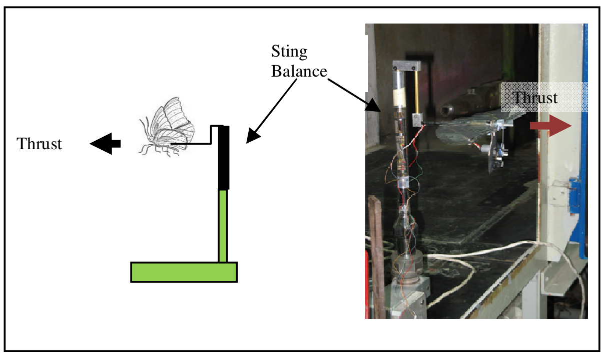

Fig. 11. Sting balance and model

The flapping frequency measurements were received through a laser pointer and a light detector. As shown in the following figure, the laser was placed near one of the wing's leading edges, where a light reflector was also positioned. Each wing pass is therefore translated into an electric pulse, which is sent to an oscilloscope connected to the laser light detector. The oscilloscope presents the incoming signal, and can calculate the pulses' cycle time and frequency.

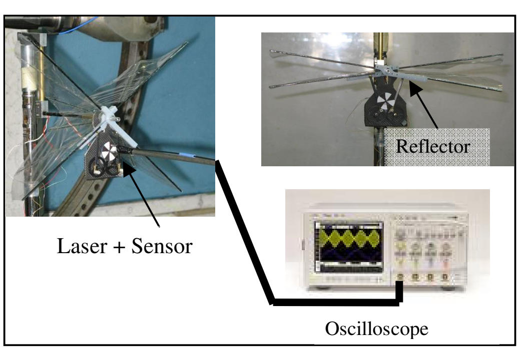

Fig. 12 Frequency measurement

The incoming voltage and current are registered directly from the DC power supply device.

Experimental results vs. theory

The received thrust from the thrust estimation theory, is presented in the following formula:

$$T_{theor} = 0.774\frac{\Phi^2 R^4}{AR}\cdot n^2 \tag{6}$$

In order to compare the thrust vs. frequency results to the theoretic curve, the results must be normalized.

The normalized thrust formula is:

$$\hat{T}_{normalized} = T_{measured}\frac{AR_{measured}}{0.774\left(\Phi_{measured}\right)^2\left(R_{measured}\right)^4} \tag{7}$$

The results were approximated as a parabolic function: $\hat{T} = Cn^2$

From this approximation the coefficient can be obtained: C=0.714

Therefore, in order to receive the results that our experiment produced, the theoretical formula needs to be corrected, by multiplying it by 0.714:

$$T = 0.714\left(T_{theor}\right) = 0.714\left(0.774\frac{\Phi^2 R^4}{AR}\cdot n^2\right) \tag{8}$$

The following figure presents all the experiment's "thrust vs. frequency" results, and it can be seen that the correction factor has indeed made the curve more compatible to the results:

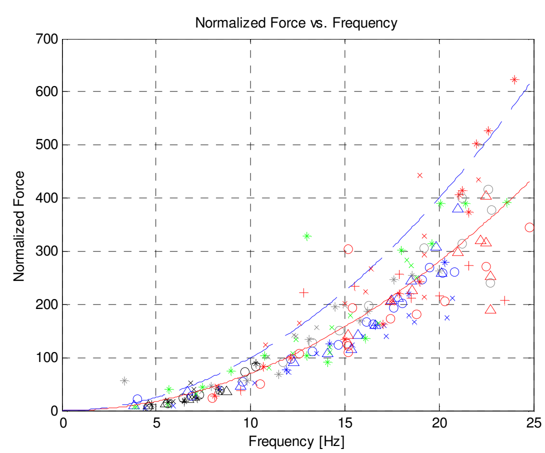

Fig. 13. Normalized force vs. frequency.

Experiment conclusions

First stage conclusions:
1. The optimal configuration that provides the biggest thrust for the frequency limit was selected.
2. It was not decided definitively which wing configuration has the highest aerodynamics or total efficiency.

These conclusions led us to pick the "extra" configuration for the next stage of the experiments.

Second stage conclusions:
1. An increased aspect ratio (for a constant area) provides larger thrust for a given consumed power and for a given flapping frequency.
2. An increase of the wing area (for a constant aspect ratio) provides larger thrust for a given total power and a given flapping frequency.
3. It seems that the preservation of the aspect ratio preserves also the aerodynamic efficiency of the wing.

Third stage conclusions:
1. An increase of the flapping amplitude provides a larger thrust (in a squared ratio) for a given power.
2. A reduction in the flapping amplitude means higher aerodynamic efficiency of the wing.
3. The total efficiency of the wing rises with the flapping amplitude.

A similarity has been found comparing the experimental results to the theory used, when a correction factor of 0.714 is applied.

5 Final Model

The final model building process was based on the conclusions from the wind tunnel experiments and engine tests. The model was influenced by insights that were acquired during the process, mainly from handling the different difficulties we came up against.

Building considerations and difficulties

The main aim is to build a low weight UAV, because we have already seen that the forces our UAV can produce are quite small (~20 gram). Moreover, during the project we decided to up the requirements, and demand a hovering capability, which demands an even lower weight.

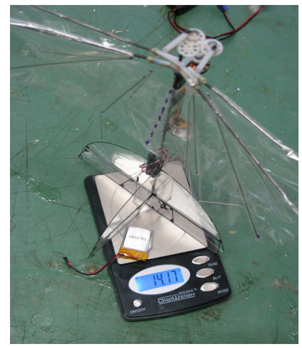

Fig. 14. Model's weight

The flapping UAV weight includes light parts such as rods, wings and cog-wheels, but the main weight comes from the motor, battery and other parts that will be specified later on.

After concluding all the parts estimated weight contribution, we found that our micro UAV estimated weight is about 15 grams.

This low weight was achieved by the use of low weight materials such as Mylar for the wings, carbon rods, and tiny low metal use cog-wheels.

The final model was built in a modular configuration, in order to make the building process more efficient. The wings, tail, and flapping mechanism were built separately, and later on were joined by a main carbon rod which constituted the UAV's body.

6 Summary and Conclusions

The presented project dealt with designing and examining a flapping winged MAV. As a part of this design, a thorough market survey was made of existing flapping MAVs and flapping wings aerodynamics. After collecting all the necessary data, a series of experiments were performed in order to check how different parameters, such as wing configuration and flapping elements, affect the flapping and its products (such as thrust and efficiency).

The first issue examined was the wing configuration and placement of the reinforcements. It was found that the area near the leading edge should be, more flexible (to allow a dynamic change of the angle of attack), and the trailing edge should be more rigid. Therefore, optimal configuration was selected for the rest of the experimental phase. After analyzing the wing proportions, the optimal wing dimensions were set: 23cm wingspan and an amplitude of 85^0.

The next step was comparing our experimental results to the aerodynamic theory and trying to validate the theory. Indeed the parameters behavior was the expected ratio, but with a correction of a constant empirical factor to the lift formula. After implementing the fixed formula, our results agreed with the expected results.

Eventually, a simple and easy flapping winged MAV analytical design tool was obtained.

In addition, a series of experiments examined a scope of efficiencies for different motors on different levels of loads, in order to optimize the chosen motor for our MAV, according to its discovered work point and MAV requirements. The optimal motor found was the LRK 10-3-32Y.

Finally an actual model was built, designed according to the conclusions reached during this project, and was even flown in the final CDR presentation in front of a live audience.

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