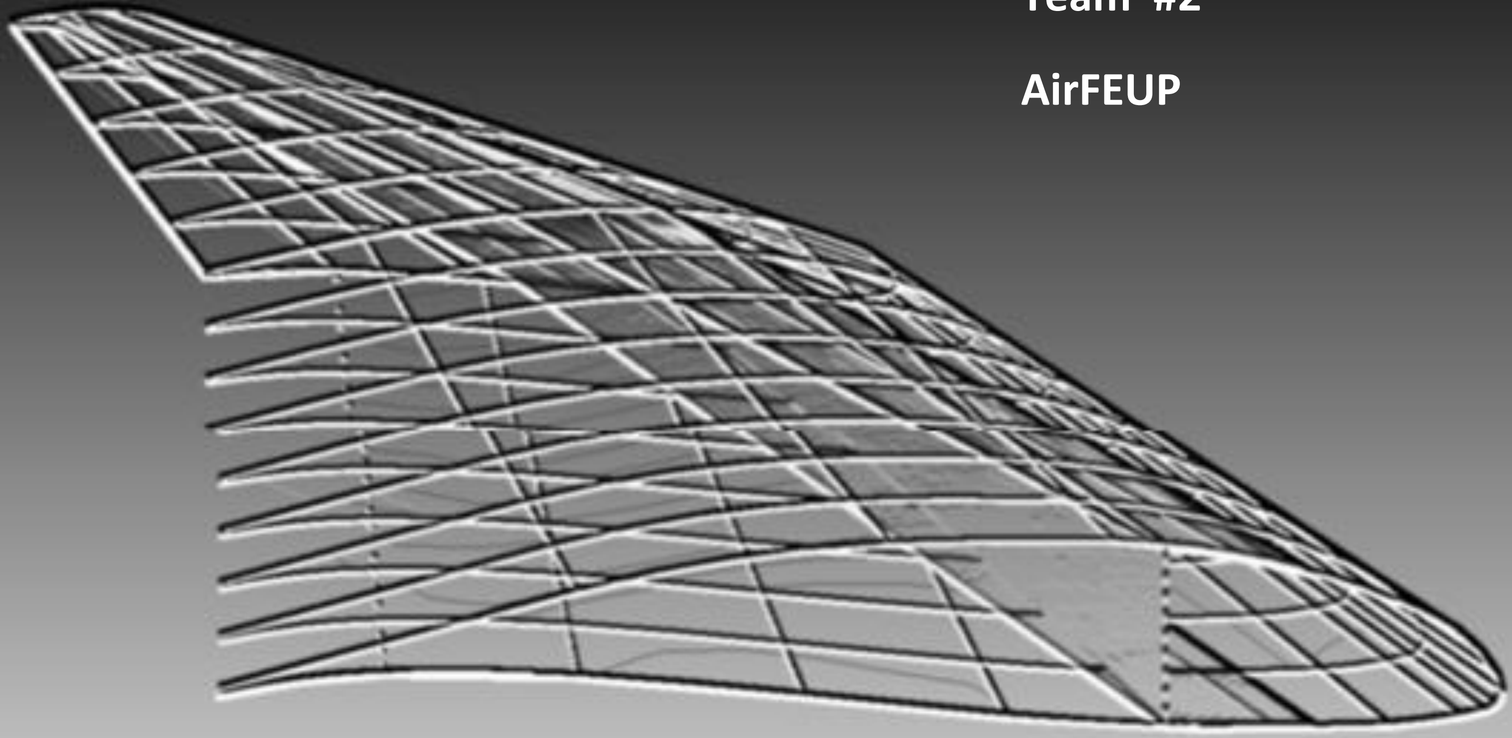
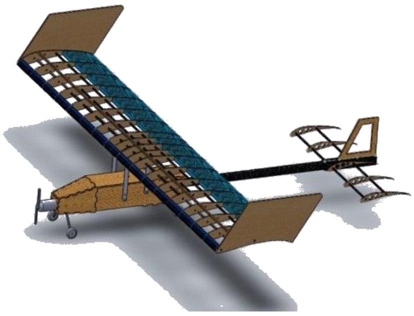
Team #2

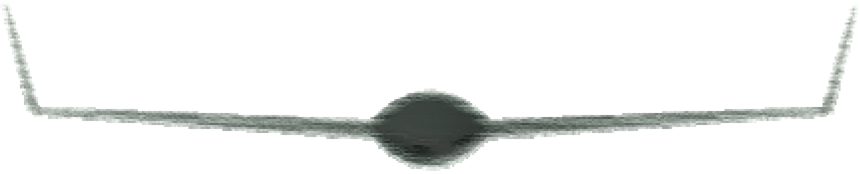
AirFEUP





NAAM

Universidade do Porto
FEUP Faculdade de Engenharia



PROJECT REPORT

Team #2 - airFEUP

FEUP – Faculty of Engineering of the University of Porto

NAAM – Núcleo de Aeronáutica, Aeroespacial e Modelismo

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1 - INTRODUCTION

Team airFEUP is a team composed of Mechanical and Electrotechnical Engineering students who are part of a group called NAAM – "Núcleo de Aeronáutica, Aeroespacial e Modelismo" (Aeronautics, aerospace and model aircraft group). We all study at the Faculty of Engineering of the University of Porto (FEUP). Currently, NAAM's only focus is the AirCargo Challenge (ACC), so all members of the group work for that project. Our aim is to build a functional prototype that is eligible to enter the ACC competition, while also trying to innovate and develop our model in order to be competitive.

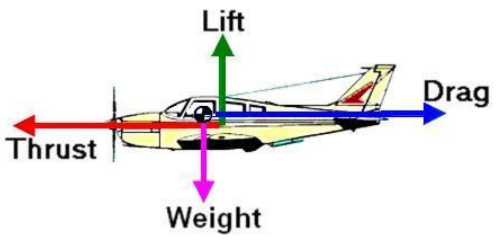
As our group is not the same as in past years, we are still gathering experience, and therefore we decided to hold a presentation of the project to first-year students, in order to create a team that can keep renewing itself and performing consistently at every edition of ACC. We hope that, with this initiative, new students with capability and will to innovate will emerge and continue to raise the bar on model plane building at FEUP.

Our plane was designed bearing in mind the design faults and the positive points of last year's project, in the hope of improving their mark and developing a more efficient prototype. By using analytical estimation we hope to have chosen a design that is adequate and well-performing.

Looking backwards to the whole process, the main prize we got from this project is the knowledge and experience in aircraft building, experience that could prove valuable as a tool for our future as engineers. We learnt how the real building process goes down, and dealing with real world problems in engineering is what we're asked to do when we leave to the work market. Moreover, the tools we gathered from the project will remain as a foundation for future competitions' projects, where we hope to improve even more our designs and predictions.

2 - CONCEPTUAL DESIGN AND LAYOUT

When we first met and started pitching ideas for the first drafts of the design, we started asking ourselves what went wrong last year. We found out that, while some points, such as wing profile, could be maintained, most of the design presented flaws to some extent. Since the objective of this contest is to carry the largest amount of weight while abiding to all regulations, our aim was to analyze and optimize each part of the plane so that it is as efficient as possible. We did this with two major constraints in mind: the first was the maximum weight of 1800g, which automatically led us to searching for weight cutting options; the second constraint was the electric motor, which is the same for all participants; with 20N of estimated thrust, we cannot expect it to lift a big and heavy aircraft. Additionally, as the whole plane needs to fit in a box to be transported, we couldn't build large, rigid parts, which are almost always beneficial in aeronautics. This is especially true for wings, as a dismountable wing will be a lot weaker than a rigid one, and will have to be heavier if we want it to maintain the physical properties of the rigid one.



Picture 1 – The forces acting on a plane during flight.

The design started developing with on simple idea in mind: to maximize the load an aircraft can carry, we need to reduce the weight of the aircraft and the drag it generates and we need to maximize the lift and the thrust it can generate (see picture 1).

The single most important part of the design of an AirCargo plane is the lift. You simply need it to be as high as possible. The first step towards that goal was to choose a wing profile that generates great amounts of lift. As most wing profiles are optimized to provide a compromise between lift and drag, we didn't have much to choose from, as drag was not really a problem for us. As such, we stuck to the profile used last year (see chapter 6). From this important decision, we began developing the concept for our plane, and in the process started drifting away from last year's model, each flaw being identified and eliminated.

3 - MATERIALS

Selecting the correct material to apply in each area of our plane is a crucial task in order to maximize rigidity and minimize weight. By researching and analyzing each of the available materials, we aimed to optimize the material selection process. This also enabled us to calculate an accurate prediction for the final weight of the aircraft.

We made a primary selection of materials from our experience in model plane building and some web research. We then proceeded to analyzing each one of them specifically, allowing us to develop a good range of solutions.

3.1 - Metals

Right from the start metals were almost put aside, and we only used them in some very specific parts like bolts and joints, and as reinforcements in some critical zones. This option was made because of the metals' high density that would jeopardize the light weight construction that we needed to achieve.

3.2 - Reinforced Fibers

Carbon and glass fibers are very popular in the aviation industry and are widely used in aircraft model construction. Their high resistance to weight ratio gives them a great advantage in structural design and project. This said, they still are quite heavy when compared to wood, which means that when going for ultra low weight we can't use them as the structural foundation of our design. Also, the costs and the processes needed to achieve good quality parts mean that we can't afford to make a whole fuselage out of carbon fiber, for example.

Comparing carbon fibers with glass fibers led us to some simple conclusions: a carbon fiber bar is stiffer than a glass fiber one with the exact same dimensions, which means that if we need a set stiffness, more glass fiber will be needed; if we now look at the thickness of both carbon and glass fiber fabric, we find that carbon fiber fabric is available to us in much lower thicknesses, which is another advantage in the quest for the lightest aircraft possible.

The main advantage of glass fiber usage is that no special machinery is needed for its conformation, as opposed to the fabrication process of carbon fiber parts, which involves vacuum bags and autoclaves.

The carbon fiber presents another potential problem: it is well known that it can produce interference in radio signals, so we can automatically exclude carbon fiber as a potential material for the fuselage, as all the electronics and the antennas will be placed in there.

3.3 - Foam

Several different types of foam were studied, being polystyrene the most common and the cheapest, as well as the lightest of all the foams we found. These materials were thought of mainly for wing shaping. Some additional research was made regarding processes of density reduction of foams during their injection. With this we hoped to find a way to make wings with internal wood structure, and foam core, achieved by a process of injection on a closed mould, with the wood structure already inside.

The biggest problems of this material are its mechanical properties. It has very low stiffness and is very fragile, making it hard to be used in any major structural component.

3.4 - Wood

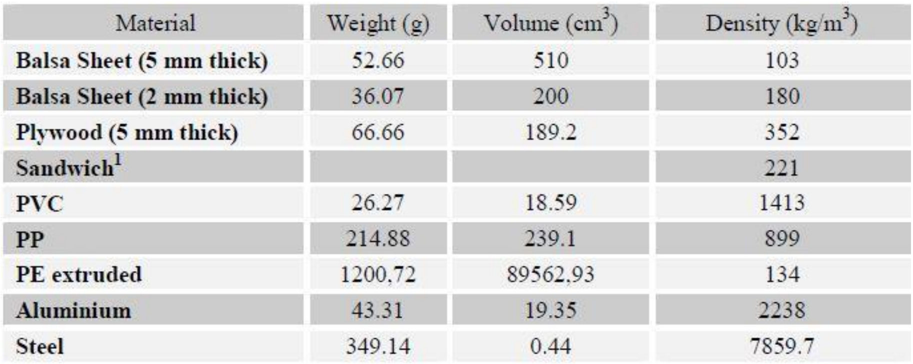
In a model aircraft, a significant part of the structure is made out of wood, usually balsa or plywood, or even a sandwich of wood with carbon fibers. Knowing this, we tried to find as much information as we could about the multiple woods existing in the market, paying special attention to their mechanical properties.

Soon we found that these materials rarely have data sheets with this information, and worse, those which had some sort of information were made by estimative, the real properties often being far from the presented values.

We then went back to the experience of last year's team, who had compiled a report with experimental results of the tests to plywood and balsa wood (see tables 1 and 2). This was a critical point in the materials choice, as we could now make informed decisions about which wood to use in which place.

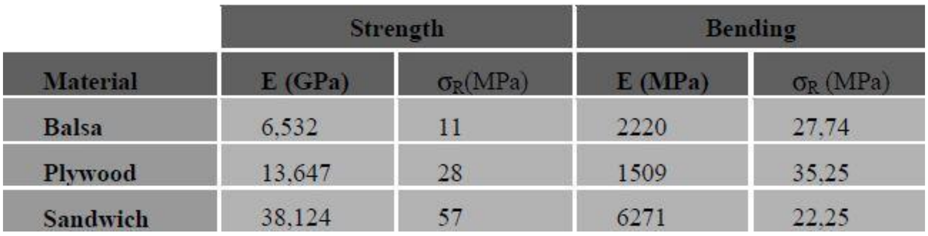
Table 1 - Weights and densities of some materials.

[1] – Sandwich is a plywood and carbon fiber sheet, with a thickness proportion of 10 to 1 plywood to carbon fiber



Material	Weight (g)	Volume (cm^3)	Density (kg/m^3)
Balsa Sheet (5 mm thick)	52.66	510	103
Balsa Sheet (2 mm thick)	36.07	200	180
Plywood (5 mm thick)	66.66	189.2	352
Sandwich[1]			221
PVC	26.27	18.59	1413
PP	214.88	239.1	899
PE extruded	1200,72	89562,93	134
Aluminium	43.31	19.35	2238
Steel	349.14	0.44	7859.7

Table 2 – Strength and bending force for balsa, plywood and a sandwich of plywood and carbon fiber.



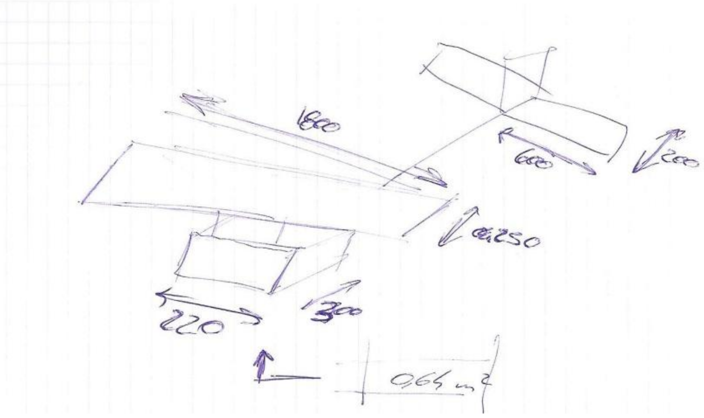
	Strength		**Bending**	
Material	**E (GPa)**	σ_R(MPa)	**E (MPa)**	σ_R (MPa)
Balsa	6,532	11	2220	27,74
Plywood	13,647	28	1509	35,25
Sandwich	38,124	57	6271	22,25

4 - DESIGN AND STRUCTURE

As we previously mentioned in chapter 2, our design development was made, in a first stage, by correcting flaws in last year's project, followed by a second stage where we tried to improve the design with our own innovations. Some made it to the final prototype; others were left behind as they proved impractical or simply useless.

4.1 - Wing

Right from the start, a priority was established: the fuselage and the wing should be two separate modules. This was a must in all the sketches we drew (see picture 2), and the final design is based on a concept of "hanging fuselage", in which the body of the aircraft hangs from the wings instead of being a part of them. This was a decision made for a number of reasons, and each of them will be described in detail.

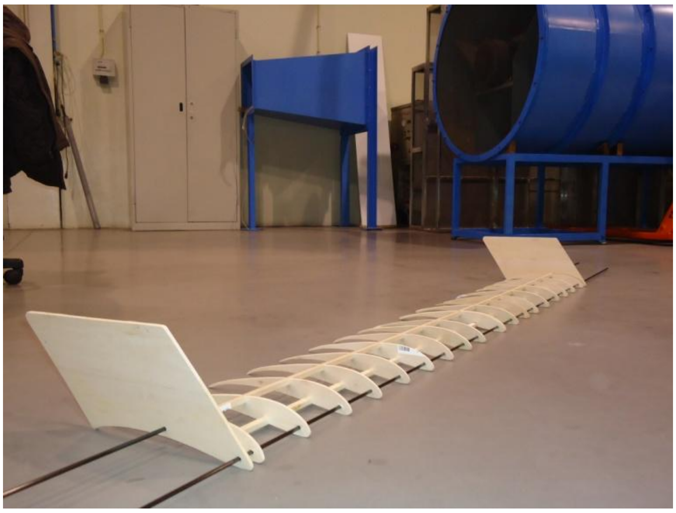


Picture 2 - A first draft of the aircraft design

First of all, a plane generates more lift if the wing area is larger. We thought that a structure similar to modern cargo aircraft, with the wings coming out of the fuselage, wouldn't be taking advantage of the area above the fuselage, and so in our design the wing functions as a whole and the airflow is not interrupted by the fuselage. The turbulent airflow created by the body will not affect the airflow of the wing, allowing for a much cleaner airflow area in the wing. This improves lift as we have a larger wing area and the airflow is not disturbed and is as parallel to the wing as possible.

In addition, having the fuselage below the wing helps us maintain stability while flying, as the flight path will be much more predictable. We are aware that we will lose a lot of on-air maneuverability, but this is not an important characteristic on an ACC plane. The weight of the fuselage and cargo will counter the forces generated by the ailerons so that the aircraft turns a lot slower than normal.

Moreover, the use of a single wing with a constant section for the whole plane helps us improve rigidity and makes the construction easier. We took advantage of this to project a dismountable wing in two modules which are easy and quick to attach to each other. This in turn allowed us to make several wings and use the



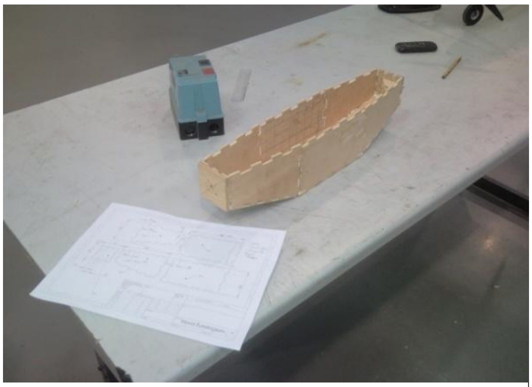
Picture 3 - The "skeleton" of our wing

best one, with the substitution being as simple as unscrewing six bolts.


Picture 4 - One of the wing profiles

The construction of each wing was quite simple, and the process was optimized so that we could “mass-produce” wings. We started by making profiles out of 5mm thick balsa wood that had the shape of our selected wing profile (see picture 4). We then drilled two holes in each profile and sanded our two squares in predefined places. The process continued with the assembly of the wing by inserting two carbon fiber rods, one in each hole. These rods are the main structural part of our wing (see picture 3). Two balsa wood strips were then glued to the profiles in the sanded squares, in order to prevent them from rotating and further improve rigidity. Two winglets were then added to minimize wingtip vortices and reduce drag.

After this we covered the wing in heat-shrinking plastic to obtain a lightweight wing with a profile close to what we predicted. For the final wing, not shown in these pictures, we used extruded polystyrene to fill the inside of the wings in order to maintain the profile as close to the S1223 we chose as possible. Only using heat-shrinking plastic led to the space between wood profiles deforming and losing the aerodynamic profile we went for.


Picture 5 - The fuselage and respective technical drawing

4.2 - Fuselage

Unlike the wing design, we didn’t pay a lot of attention to the fuselage, and we focused solely on creating a sturdy base where the cargo could be held and that wouldn’t create a lot of drag. Our fuselage is a simple box made out of plywood (we chose it for its strength, in order to securely hold all the electronic components and the cargo, in addition to holding the tail boom in place) with an open bottom allowing an easy access to the cargo bay. We glued the plywood walls by cutting ribs in the wood (see picture 5) which maximize the contact surface between walls in order to make a sturdy fuselage.


Picture 6 - The assembled plane

The fuselage is connected to the wing through the use of four carbon fiber bars, which ensure the rigidity of the connection and distribute the weight evenly between both halves of the wing;

the front landing gear is screwed to the fuselage through a raiser, as with the original height the propeller hit the ground (see picture 6).

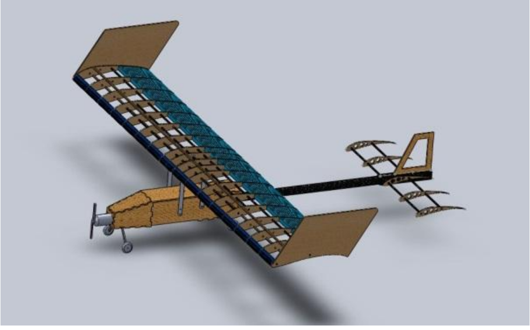
4.3 - Tail

Our aircraft's tail boom is quite simple. A carbon fiber fishing rod connects the tail to the fuselage and the control surfaces are built using the same process as the wing. In order to increase lift, we decided to make the horizontal stabilizer with a profile similar to the wing. We hope that it helps take some load off the wings and enables us to lift more weight. The fin is milled out, so that it is only a spine covered in heat shrinking plastic, in order to save weight.

4.4 - The final plane

Our final aircraft for the competition is a very simple high wing cargo plane, bearing some resemblance to the iconic Piper J3 Cub (see pictures 6 and 7). Although it might seem just pure coincidence and color choice, there is a reason for that. The J3 is known as the most popular light aircraft of all time, even drawing comparisons as the "Ford T of aircraft". Its simplicity made it an excellent flight trainer for new pilots. Our plane is also focused in ease of maneuverability and construction, so is isn't hard to see that they share more than the color.

Picture 7 - The Piper J3 Cub



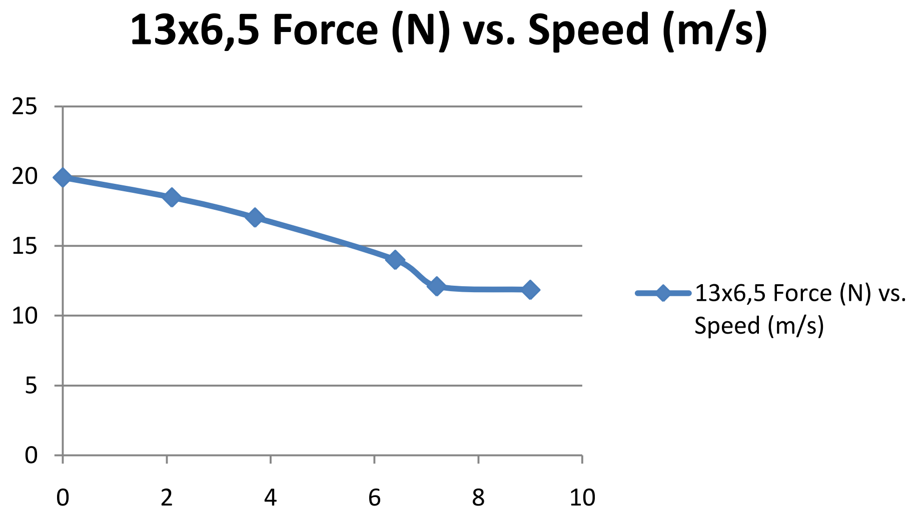
Picture 8 - A Solidworks render of our model

5 - MOTOR AND PROPELLERS

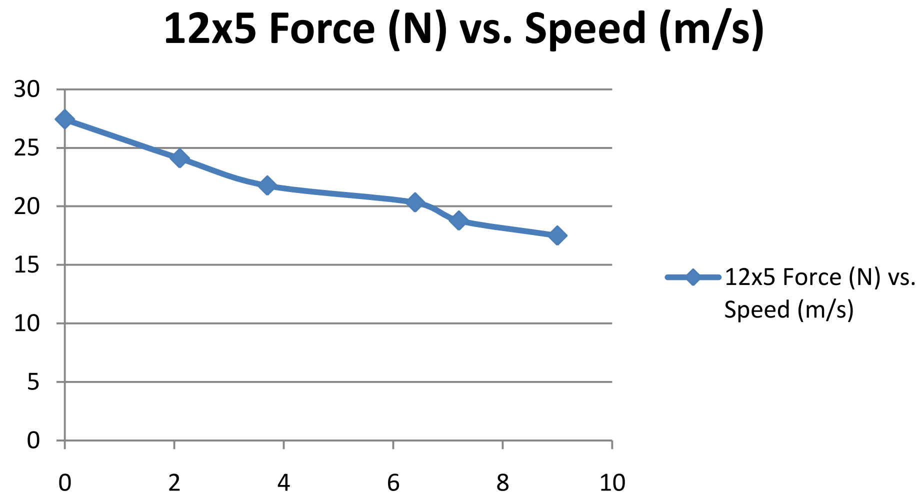
As the motor will be the same for every participant on the event (Axi Gold 2826/10), the only way to maximize thrust is to use the most efficient and adequate propeller available. In order to test our propellers, we developed a test bench based on the one used by the team last year, which used a force transducer to create a thrust vs. airspeed graph for each propeller (see pictures 9 and 10).

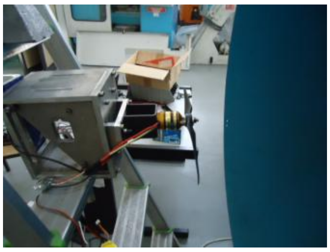
By testing with several propellers, we achieved a value of about 20N as the thrust of the propeller with no wind speed. We then proceeded to use the wind tunnel to generate various wind speeds (see picture 10), and for each one we took readings of the thrust the motor generated with each propeller. The wind speed was measured using a portable anemometer and the force was measured using the aforementioned force transducer mounted in a rig which was purpose-built for testing this motor.

At the time of writing, the testing was in progress but not already finished. Our supplier didn’t have the propellers we asked for, and as such we are still waiting for them to arrive to test each of them. We have already tested a 13x6,5 and a 12x5, and the results are promising, as we are achieving solid readings with no values off the chart. We will also use the recommended propeller for this motor, the 11x8.



Picture 9 – Our testing rig in front of the wind tunnel





Picture 10 – Close-up of the motor and the force transducer rig

6 - AERODYNAMIC DESIGN

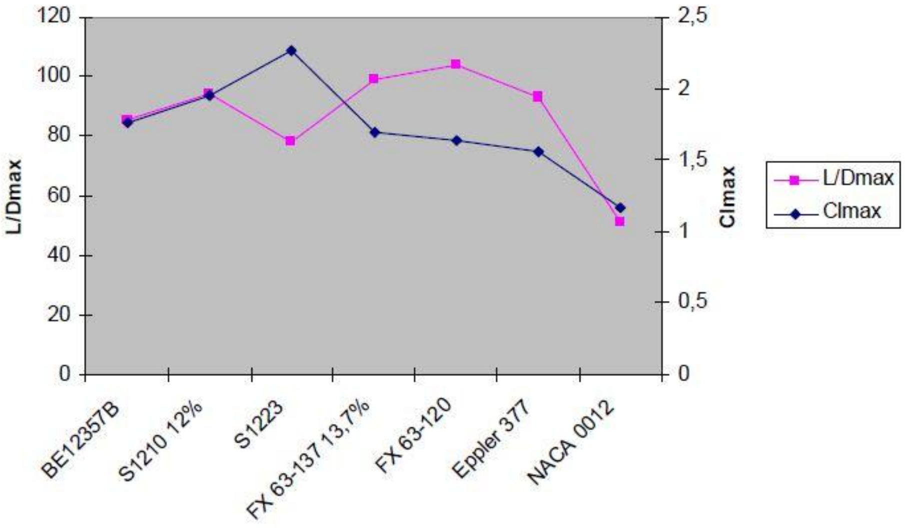
6.1 - WING

6.1.1 - Optimization factors:

Lift-off distance ≤ 60 m
Mpayload = Mtotal - Maircraft [kg]
Payload score = 20 x Mpayload [points]

6.1.2 - Airfoils

We used *Profilli* to analyze the various airfoils, selecting some of the common airfoils and the ones with higher lift (see picture 7). We can conclude that S1223 airfoil, although not the most balanced, it is the most suitable for the application in analysis, as the high lift it generates is critical to achieve a good final result, and the subsequent drag is not a problem for us, as the plane does not need to be fast. This was the same profile used last year



Picture 11 - Airfoil comparison

6.1.3 - System dynamics

During the lift-off we have 4 main horizontal dynamic components: the airplane inertia, the aerodynamic drag, increasing with speed and lift, the rolling drag and the propulsion system thrust.

$$M_{total}.\ddot{x} + \frac{C_d.\rho.S.\dot{x}^2}{2} + F_{\eta-rolamento} = F_{motor}$$

The rolling drag depends on the 2 vertical dynamics components: airplane weight and aerodynamic lift.

$$F_{\eta-rolamento} = \eta.(g.M_{total} - \frac{C_l.\rho.S.\dot{x}^2}{2})$$

6.1.4 - Lift-off distance

The lift-off happens when the speed is enough to generate enough aerodynamic lift to counter the aircraft weight. We know that more lift is created when the airplane pitched to stall attitude. So, the minimum flying speed is the stall speed, making the lift-off speed:

$$V_{LO} \approx 1{,}1.V_{stall} = 1{,}1\sqrt{\frac{2}{\rho_\infty}\frac{W}{S}\frac{1}{(C_L)_{\max}}}$$

With this in mind Anderson presents the following method to determine the lift-off distance.

$$s_g \approx \frac{1{,}21(W/S)}{g.\rho_\infty(C_l)_{\max}\left[T/W - D/W - \mu_r(1-L/W)\right]_{0,7V_{LO}}} + 1{,}1.N\sqrt{\frac{2}{\rho_\infty}\frac{W}{S}\frac{1}{(C_l)_{\max}}}$$

Where T, the thrust, D, the aerodynamic drag, and L, the aerodynamic lift, are evaluated for 70% of the lift-off speed (VLO). N is the time taken by the airplane to rotate to the stall angle.

6.1.5 - Corrections

The data obtained from *Profilli* is for 2D airfoils or infinite span wings. To obtain the actual lift of the airplane, we made:

$$a = \frac{a_0 \cos\Delta}{\sqrt{1+\left[(a_0\cos\Delta)/(\pi AR)\right]^2} + (a_0\cos\Delta)/(\pi AR)}$$

Where the real slope of the lift coefficient curve (a) is calculated with the theoretical slope of the lift coefficient curve (a0), the Aspect Ratio (AR) and the sweep (D).

To the original drag coefficient we need to add the induced drag, the drag created by the landing gear and the parasite drag. The induced drag is created by the tip flow, and this is increased with lift.

$$C_{Di} = G\frac{C_L^2}{\pi \cdot e \cdot AR}$$

G is the ground effect, which tends to decrease the induced drag.

$$G = \frac{(16h/b)^2}{1+(16h/b)^2}$$

The landing gear aerodynamic drag is decreased with flap deployment. Anderson provides the following equations for calculating this drag amount.

$$\Delta C_{D,0} = \frac{W}{S} K_{UC}.m^{-0,215}$$

In Anderson the recommended volume coefficients are,

$$V_h = \frac{l_h.S_h}{\bar{c}.S} = 0,7$$

$$V_v = \frac{l_v.S_v}{b.S} = 0,04$$

6.2 - AIRCRAFT PERFORMANCE

In order to obtain the payload capacity at various heights we need to vary the air density and acceleration of gravity in the calculation of the need distance to take-off. To do that we used the next two formulas,

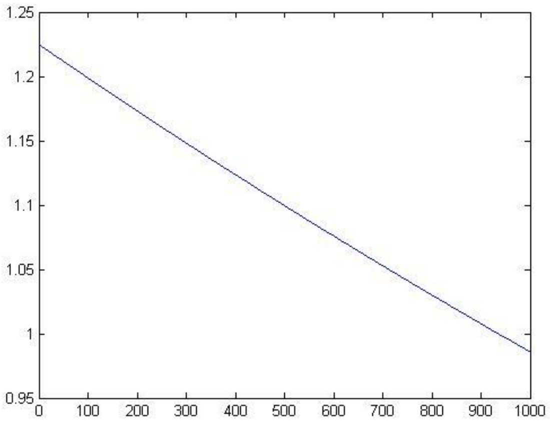
$$\rho = 352,98360\frac{\left(1-2,25577\cdot 10^{-5}\cdot H\right)^{5,25589\left(\frac{6371020}{6371020+H}\right)^2}}{\left(288,15-0,0065\cdot H\right)}$$

$$g = 9,80665\cdot\left(\frac{6371020}{6371020+H}\right)^2$$

From those, we were able to plot a graph that relates air density with altitude (see graphic 1).

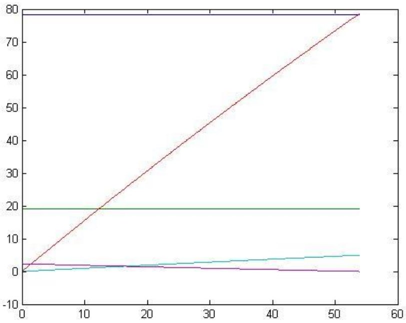
We then proceeded to create a prediction based on a total mass of the plane of 8 kg (1,8kg plane + 6,2kg cargo). With this we achieved a graphic that gives us the intensity of the forces acting on the plane during lift-off (see graphic 2)

From this force graph we could now conclude how the speed would vary in a 60m runway. We plotted a graphic with this information (see graphic 3) and compared it with the lift-off speed we got from the equation of the stall speed. We could now conclude that our airplane will theoretically lift 6,2kg of cargo. Finally, and in compliance with regulations, we plotted a graphic that relates air density with the predicted payload capacity (see graphic 4).

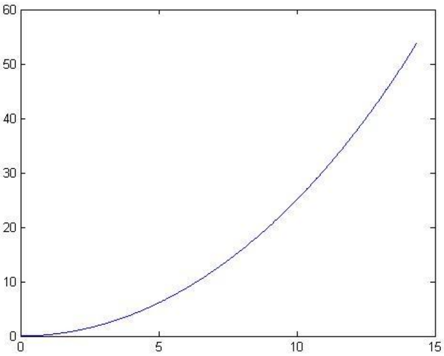


Graphic 1 – Air density (kg/m^3) vs Altitude(m)

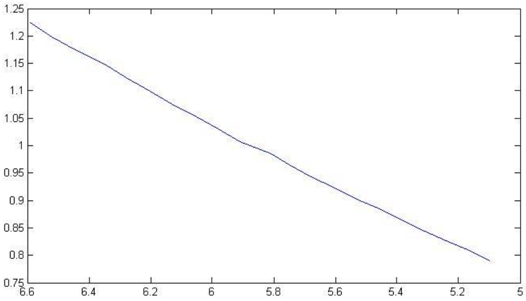
The problem, though, is that we know from some simple tests made to the final plane that the cargo value will be limited by the structural resistance of the aircraft, and we think that 4 to 5kg is a more accurate figure.



Graphic 2 - Forces acting on the plane [N] (navy blue: weight; red: lift; green: thrust; light blue: drag; purple: friction) vs. Distance (m)



Graphic 3 – Velocity (m/s) vs. Distance (m)



Graphic 4 – Payload (kg) vs. Air density (kg/m^3)

7 - Conclusions

Building an aircraft involves two major phases: the modeling, simulation and analysis part, essential to ensure a well-balanced and flying aircraft, and the actual building, where precision and patience are key, as at this time the plane cannot get any better than in theory, but it certainly can get worse. Both stages of our project proved to be invaluable experience to us as engineers, and this is probably the most important part of the project for us. Aviation is an area which you've got to love if you want to go any further than a paper plane.

Our aircraft is designed in a simple fashion so that the lack of free time available to the team did not jeopardize the construction. It is so simple that anyone could come by the laboratory and cut profiles or drill holes, ensuring that everything was completed on schedule.

To sum up, our aircraft is aimed at obtaining a good place in the final competition, and we predict that it will ultimately prove our worth as engineers and builders. The difficulties we have overcome to achieve this final result are essential as part of our learning process and have made us better students.

8 - Bibliography

1. Anderson, John - Aircraft Performance & Design, McGraw-Hill, 1998

8.1 – Software

1. Solidworks 2012
2. MATLAB R2010b
3. Profili 1.67

9 – Attachments

1- Isometric View
2- 3-View Drawing
3- Cargo Bay Location
4- Cargo Bay Dimensions