ESTACA

Mini-Bee project report

Promotion ISPEB

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Acknowledgments

First, we would like to thank our tutor, Mr Xavier DUTERTRE, CEO and founder of TECHNOPLANE and director of the Mini-Bee plane project. Indeed, his availability, knowledge, advice, as well as the sharing of numerous documents all year round allowed us to move forward and to achieve, despite the difficulties, our final objectives concerning this project.

We would also like to thank Mr RIZOUG for his assistance on this project whenever we needed some. Finally, we would like to thank and congratulate all the other teams that are working and have worked on this project. All the research they have done and made available for us have been of great help.

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I. Introduction

As part of our last year of studies in ESTACA and being specialized in propulsion system integration and on-board energy, we worked on a project named Mini-bee. This research and development project, launched in 2015 and led by Xavier Dutertre the director of the company TECHNOPLANE, is collaborative. Indeed, other schools (Supméca, ENSEA, Politecnico Di Torino, Centrale SUPELEC) and industrialists (ALTEN) participate in the development of this aircraft. The Mini-Bee is made in this context of exploration of news ideas, in order to discover other aircraft concepts and means of propulsion.

This year, we worked on a demonstration version of the Mini-Bee. This version is designed for only two people and is propelled principally by the combustion engine Rotax 914.

Our group had to dimension the motorization around this engine. We had to dimension and select the different components of the propelling system. To complete this task, we used the work reports done during the previous years by the other students on the structure and the characteristics of the Mini-Bee.

In addition to the Rotax 914, batteries and a turbine created by the start-up Turbotech will provide enough energy to power the rotors and the propellers.

1. Mini-Bee concept

The road traffic will become a growing issue in our ever-expanding cities. People spend more and more hours in their cars coming home from work, emergency services get stuck and cannot arrive on site in time. The Mini-Bee could solve this issue.

The Mini-Bee is a hybrid personal aircraft (VTOL Hybrid Octocopter), which uses electric engines during the different stages of the flight. It is a combination of an airplane, a helicopter and a drone. It takes all the advantages of each and none of their drawbacks. It should cost the same price as a helicopter and be capable of high-speed flight like an airplane. Indeed, it presents features of high mobility comparable to helicopter and has a VTOL capacity (Vertical Take-Off and Landing).

Here are the main characteristics of the Mini-Bee:

Characteristics	Value
Maximum mass (kg)	700
Cruise speed (km/h)	220
Maximum speed (km/h)	300
Maximum altitude (m)	4000
Climb speed (m/s)	5,5
Fuel range (km)	600
Autonomy	3h
Price (€)	250 000

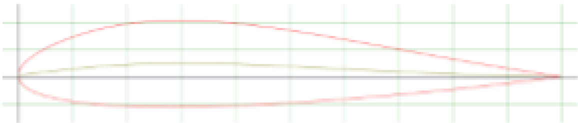
2. Comparison of the characteristics of the Mini-Bee

	Mini-Bee	**Cessna 152**	**Robinson R22**
Empty mass (kg)		518	399
Maximum mass (kg)	700	757	622
Cruise speed (km/h)	220	198	177
Maximum speed (km/h)	300	276	189
Maximum altitude (m)	4000	4480	4267
Climb speed (m/s)	5,5	3,63	6,1
Fuel range (km)	600	1278	386
Autonomy	3h	8,7h	3,5h
Price (€)	250 000	39 420	210 148

II. Analysis of the resources and constraints of the Mini-Bee

1. Aerodynamics hypothesis

The Mini Bee's wings are designed as the Davis B-24 profile. Their lift cruise coefficient Cz is 0,78. With a 700 kg MTOW, its relative weight is around 6867 N.



Davis B-24

Therefore, we are looking for a wing area that would make this lift equal to its weight at 220 km/h in the worst case of utilization: at the altitude of 4000 m where the air density is the lowest.

Then, we can calculate this area thanks to this formula:

$$F = 0{,}5 \times \rho \times S \times Cz \times V^2$$

Values:

$F = 6867\ N$

$Cz = 0{,}78$

We find an area $S = 5{,}8\ m^2$.

Nevertheless, if we want the Mini-Bee to fly at lower speed and climb with a 10° angle without the intern rotors, we need to have a wider wing area. Therefore, we choose an area of $7\ m^2$.

Concerning the drag-cruise coefficient, we kept the value found by the former working group: $Cx = 0{,}05$. Now, we must estimate the frontal area of the cockpit. Our version of the Mini-Bee is designed for 2 peoples and we know that a classroom table for two measure around $1{,}18\ m$ for its longest edge.
Therefore, we estimate the frontal area of the cockpit at $1{,}4\ m^2$ because this surface corresponds to a square with $1{,}18$-meter sides.

We finally have a total frontal area of $8{,}4\ m$ to calculate the drag.

2. Mini-Bee mass assessment

The Rotax 914 can provide a maximum power of 85 kW. To ensure the security of our system, we choose to keep a safety margin of 20 kW which allows us to avoid the possible errors due to simplifying assumptions. We decided that the sum of the battery power and the power supplied by the Turbotech turbine cannot exceed 80 kW. Therefore, the association of these two power sources will supply only 60 kW. The total power enable during the takeoff phase will be of 145 kW.

For the vertical speed of the Mini Bee, we choose a value of 20 km/h because this speed allows to reach the cruise altitude (1000m) in 180 seconds which matches with our boost period. Concerning our horizontal speed, it corresponds to the speed of a tour helicopter: 200 km/h.

Thanks to this information and the excel file created by the former working group, we were able to iterate the mass of our Mini Bee to estimate the MTOW in the worst case of utilization. Thus, we find a MTOW of 700 kg.

Input							
Speed (km/h)	Altitude (m)	Climb angle (°)	Mass	Diameter		Number of propellers	
				Intern	Extern	Intern	Extern
20	1000	90	700	1,4	2	6	4

Output						
Thrust per propeller (N)		Power per engine (kW)		Max rotational speed (tr/min)		Total Power (kW)
Intern	Extern	Intern	Extern	Intern	Extern	
693,7	693,7	15,7	11,2	3926,6	2748,6	139,2

3. Presentation of the Rotax 914

The demonstration version of the Mini-Bee will be powered by the Rotax 914, a combustion engine, during the horizontal flight and by batteries during the vertical flight.

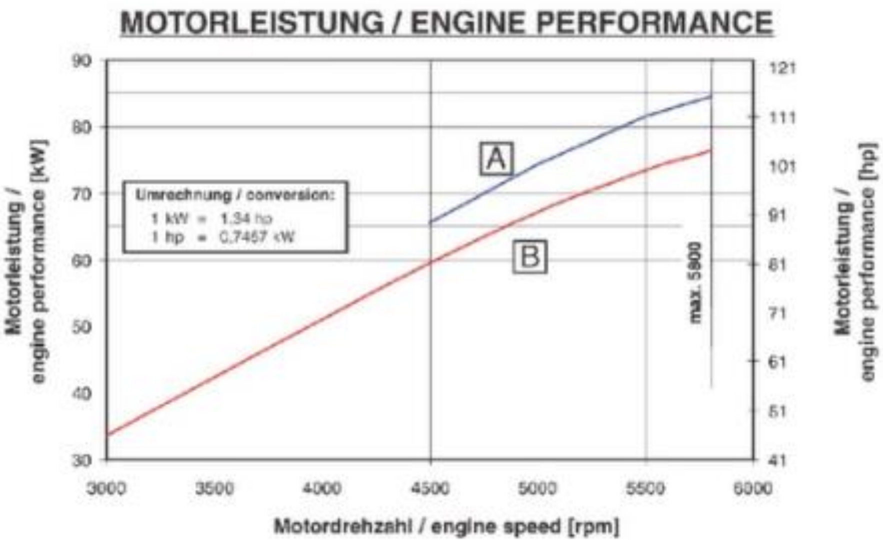
The Rotax 914 is a four-cylinder engine with a turbo charger. It can provide a power of 73 kW in continuous operation and, thanks to a turbo, a power of 85 kW during 5 minutes.

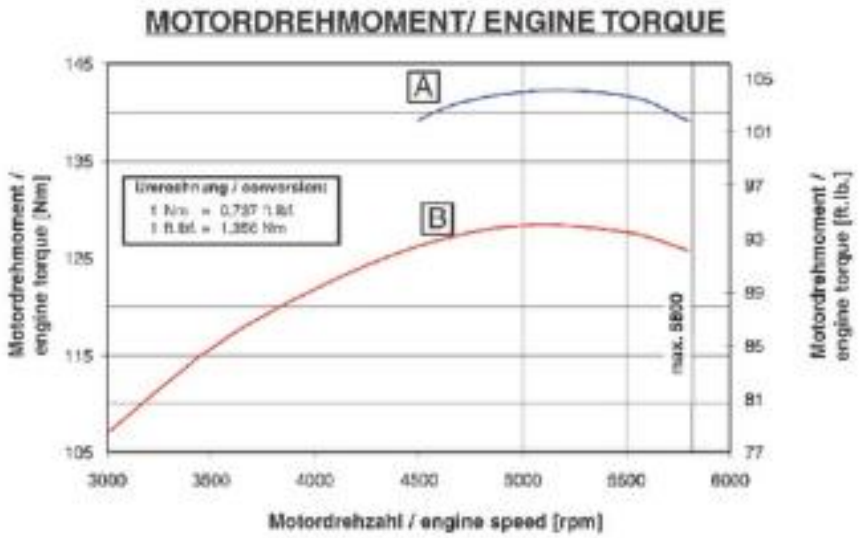
The main characteristics of the Rotax 914:

Rotax 914	
Characteristics	Value
Weight (kg)	74,7
Torque (Nm)	144
RPM (tr/min)	5800
Price (€)	28000

This engine offers better performance at high altitude and high speed as we can see in the next graphics. It presents the engine performance, the engine torque and the fuel consumption as a function of engine speed:

<u>Nota Bene:</u> The A curves represent the take off-phase, the B curves represent the maximal continuous phase.





These two graphics show us that the takeoff phase is more powerful than the continuous phase. We choose this engine because it is very important for us to be able to provide more energy in a short period of time.

4. Turbotech turbine

Using lithium batteries is a cheap way to store electric power but they are not really optimized for aircrafts. Lithium batterie's power-to-weight ratio goes from 100 up to 250 Wh/kg which is low compared to what we need in order to power our motors.

We chose to focus on Turbotech, a French start-up which developed a turbo generator for small aircraft. "With 40 kg of fuel, this turbine performs equally well as 1 ton of lithium batteries" says Damien Fauvet, co-founder of Turbotech. We intend to remove 55 kW of batteries and replace them with this turbine.

This turbine will also power the aircraft. The turbine is already equipped with a rectifier (AC/DC converter) which converts the alternating current produced by the turbine into direct current. This direct current will then power the electric motors.

Using this turbine instead of batteries is going to save some space and mass in the aircraft and at the same time enhance the propulsion system's performance.

Here are some technical data about this turbine:

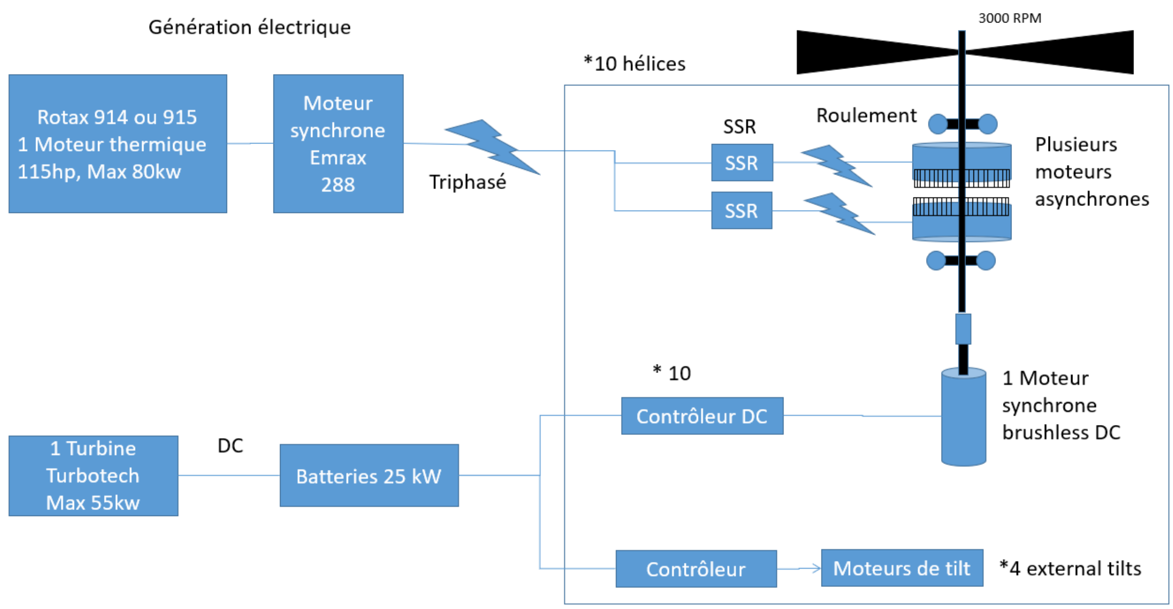
- Weight: 50 kg
- Power: 55 kW
- Fuel consumption: 15L/h
- High energy-density (power-to-weight ratio): over 2000 Wh/kg
- Price: 50 000 €

Its main drawback is its price. Indeed, the batteries which could replace it would be cheaper, but this turbine has a better power-to-weight ratio and provides more safety in the system.

III. Configuration and technical solution

1. Explanation of the architecture of the motorization

Considering the full architecture of the motorization, we choose to stack several asynchronous motors:



The main source of power in our architecture is the Rotax 914. It powers the Emrax 288 which powers the asynchronous motors.

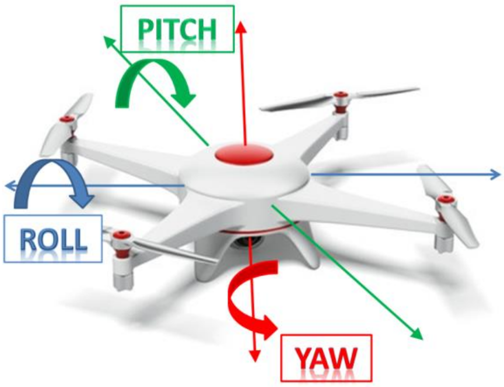
The other source of energy is the Turbotech turbine. It powers the batteries, the controllers and the brushless motor.

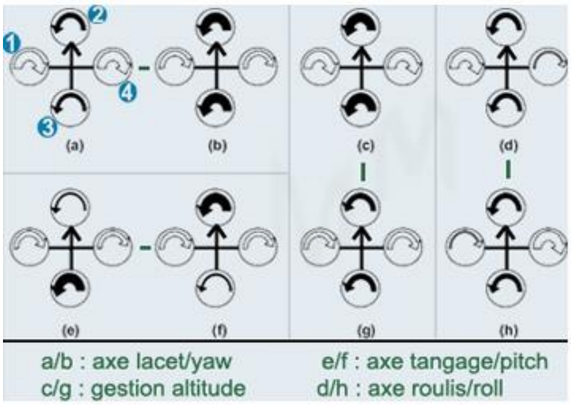
The stacking of the asynchronous motors and the SSR relays allows command them thanks to an on/off switch and decide to turn on them or not.

The continuous motor can adjust the rotational speed and provide a boost to the rotors during the vertical takeoff phase. Each external rotor is paired with four piled motors which can produce 20 kW and each internal rotor is paired with three piled motors which can produce 15 kW.

2. Vertical flight mode

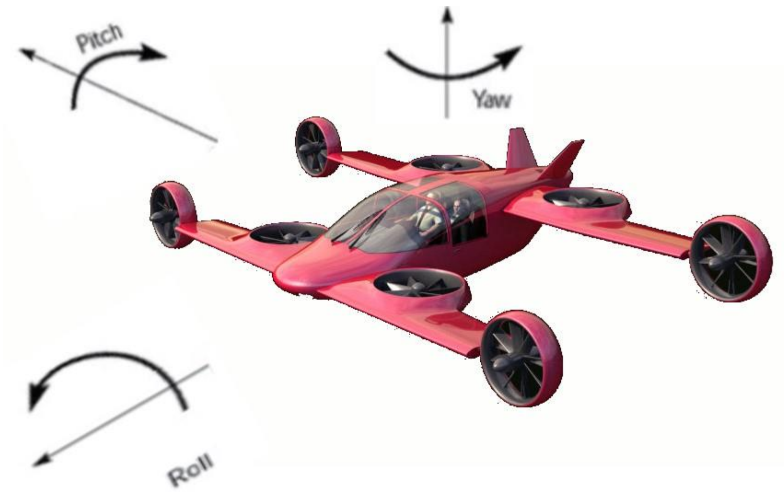
In the vertical flight mode, the Mini-Bee is controlled like a classic drone. Each motor turns in the contrary rotary way of the motors on its left and right. Like that, it can be controlled by the four external motors. To increase the thrust and take off, the rotational speed of all the motors must be increased. To move in the horizontal plan, we have to reduce the rotational speed of two motors and increase the speed of the two other motors which are on the opposite direction. This command tilts the aircraft on the axis of pitch and roll to allow a horizontal displacement. To have a rotation on the vertical axis, let’s say clockwise, we must reduce the rotational speed of motors which turn clockwise and increase the speed of the others spinning counter clockwise. All this controls can also be done with the same practice thanks to the internal rotors.





3. Horizontal flight mode

Only external motors turn in this mode. The motors are horizontal, and the rotors are vertical thanks to the tilt motors. For the yaw, we can reduce the motors' power of the side where the Mini-Bee turn and increase the power of the opposite side motors. For the roll, the motors of the side which go up are tilted to increase the lift. A half-tilted motor has its vertical vector of the thrust not null. It is the same for the pitch with front motors or back motors. To increase the incidence angle, we tilt the front motors. This last control is very important for the Mini-bee's lift because its angle of incidence is a parameter for wing's lift. Indeed, there is no mobile surface on the wings, so the lift depends of incidence and speed.



4. Transitional flight mode

During the transition between vertical and horizontal flight, the external rotors are progressively tilted in the vertical position in order to get a horizontal thrust and still produce lift. Indeed, during the transition, the Mini-Bee's speed is too low to have lift thanks to the wings. Like that the Mini-Bee accelerates horizontally and we reduce the speed of internal rotors because the airfoil's lift increases. When the external rotors are completely tilted, and the speed is enough to have the airfoil's lift we need, internal rotors are switched off and Mini-Bee flies like an airplane. To switch from horizontal to vertical flight mode, the same process must be done in reverse.

IV. Sizing the electromechanical chain

1. Power distribution

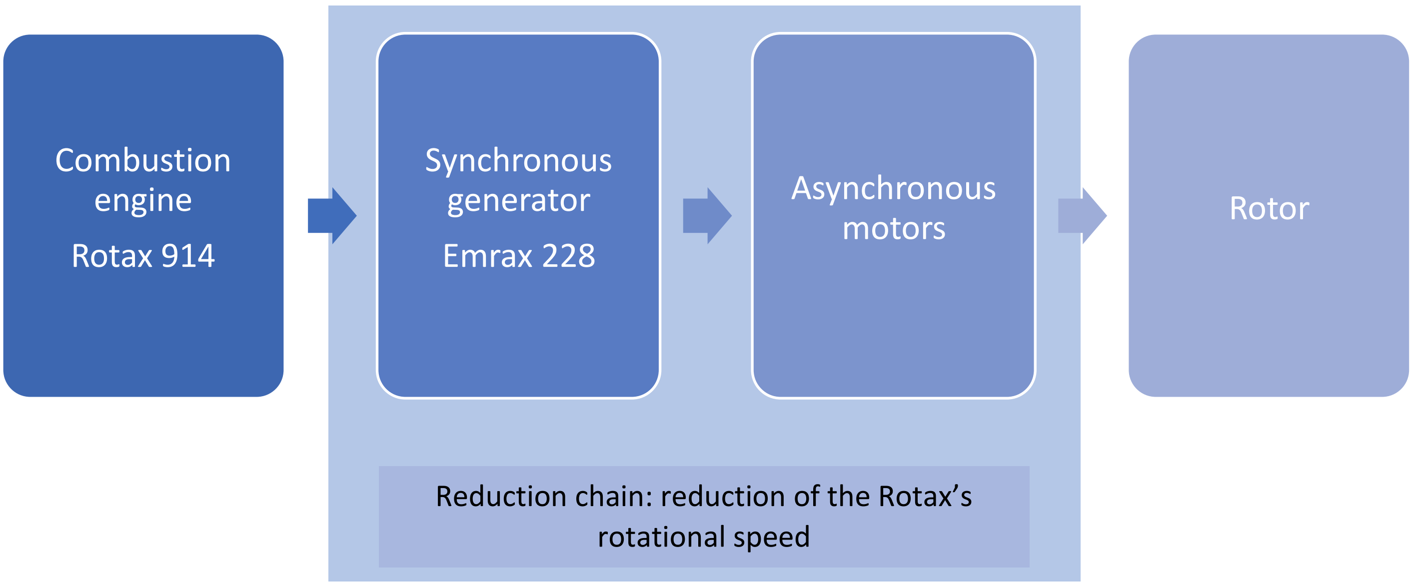
During horizontal flight, external rotors use alternating current produced by the Rotax 914 and its generator Emrax. All the movements of the Mini-Bee are controlled by continuous current motors alimented by batteries which can be recharged by the Technoplane's turbine. During the vertical flight, only continuous current motors turn on the external rotors. Internal rotors use alternating current produced by the Rotax 914 and its generator Emrax and are helped with continuous current motors. The turbine and the batteries produce all the continuous current.

2. Dimensioning the asynchronous motors

We need to dimension the asynchronous motors from the characteristics of the Rotax 914 and the rotors. We will do this study for two different sizes of blades.

Rotax 914:
- Maximum rotational speed Ω_{max} : 5800 rpm

Rotors:
- Blade diameters: 2m, 1.4m
- Maximum rotational speed N_{max}: 2000 rpm for the 2m and 3000 rpm for the 1.4m (The blade tip must not exceed Mach 0.65).



We need to determine the properties of our motors from the characteristics of our Rotax 914 and our rotors. We first need to evaluate the maximum frequency (F_{max}) delivered by the generator when the Rotax 914 is running at maximum speed. Then, knowing the rotor's maximum rotational speed (N_{max}) and the maximum frequency delivered by the generator (F_{max}) , we will evaluate the pair number of poles of the motor (P_m).

a. Asynchronous generator's frequency

The rotational speed of the generator and the motor depends on the rotational speed of the Rotax 914. The current frequency generated by the Emrax 228 (F) depends on its pair number of poles (P_g) and on the rotational speed of the Rotax 914 (Ω).

$$F = P_g \times \frac{\Omega}{60} \qquad F_{max} = P_g \times \frac{\Omega_{max}}{60}$$

P_g: pair number of poles of the Emrax 228
Ω_{max}: Rotax 914's maximum rotational speed (rpm)
F_{max}: maximum frequency delivered by the generator

$$F_{max} = 10 \times \frac{5800}{60} = 966.6\ Hz$$

b. Asynchronous motor

We now evaluate the pair number of poles of the motors, knowing the maximum frequency of the generator (F_{max}), the slip g, and the maximum rotational speed of the rotor (N_{max}).

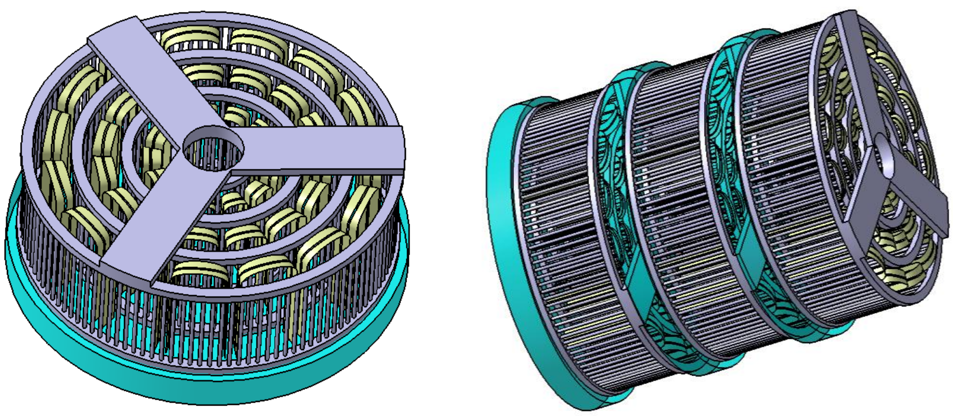
$$\mathrm{N}_{max} = (1-g) \times F_{max} \times \frac{60}{P_m}$$

g: slip
P_m : pair number of poles of the motor
N_{max}: rotor's maximum rotational speed (rpm)

$$P_m = (1-0.05) \times 996.6 \times \frac{60}{2000} \approx 27$$

So, our motors need 27 pair number of poles for a rotor with 2m blades.
If we chose the 1.4m blades, the pair number of poles would be 19.

The Rotax 914, the Emrax and the rotors will be bought. We will manufacture the asynchronous motors using 3D printing. Each motor produces 5 kW and we can stack them if we need more power. Compared to synchronous motors, these asynchronous motors are lighter, cheaper and need less maintenance. Moreover, with this configuration, we do not need to use AC/DC converters or ESC. The continuous motor can adjust the rotational speed and and provide a boost to the rotors during the vertical takeoff phase.

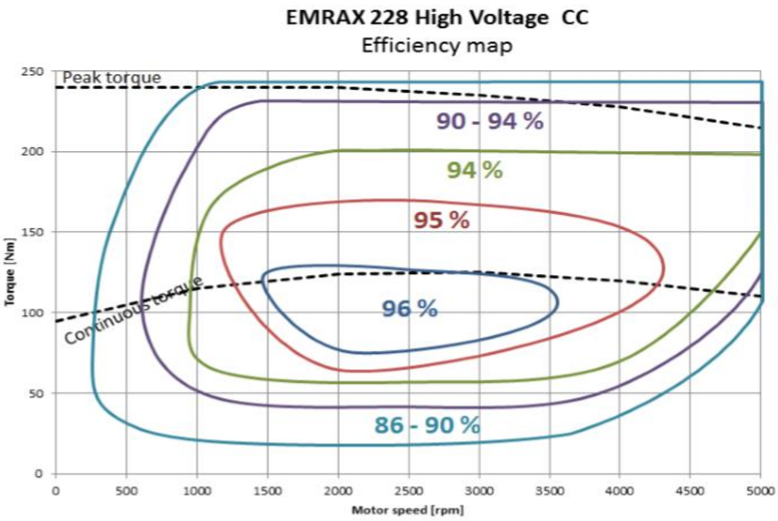


3. Choice of the generator: Emrax 228

The Rotax 914 will provide energy to power a current generator. We choose to use a generator Emrax 228. As we can see in the next table, its characteristics match perfectly with our engine:

	Rotax 914	Emrax 228
Maximum power (kW)	85	100
Maximum speed (rpm)	5800	6500
Maximum torque (Nm)	144	240
Continuous torque (Nm)	127	125

This generator has also an efficiency of 94% in our area of use as we can see in the next graphic:



It weighs only 12.3 kg which is a plus for the performance.

4. Rotor choice and sizing

a. Creation of a data base for internal and external rotors:

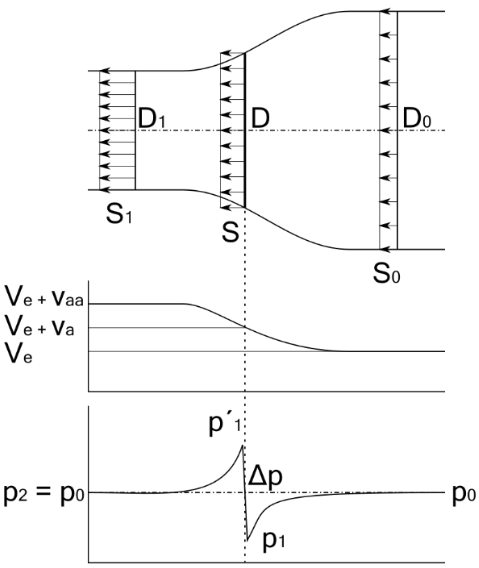


Figure 1 Momentum theory principle

In this part, we will determine the thrust and the power needed to be provided to each engine during different flight phases. To do so, we used the momentum theory. Because we do not have any data on our rotors, we need to calculate the thrust, the power and the couple as a function of the rotation speed of the engine, the Mini-Bee's speed, the blade angle and the altitude. With those data, we will be able to know the characteristics of the rotors and so if our engines are appropriate. We will use the NACA – 640 report.

We used hypothesis in order to simplify the research. We will use a twin rotor with a Clark Y profile.
The tip speed must not exceed 0.65 Mach to avoid too much noise.
We will study the two-meter diameter rotor on specific range:

- Min-Bee's speed: 20, 50, 100, 150, 200, 220 km/h;
- Rotational speed 500, 1000, 1500, 2000 rpm;
- Altitude: 0, 500, 1000, 2000, 3000, 4000 meters;
- Blade angle: 20, 25, 30, 35, 40 deg.

The rotational speed limitation is due to the tip speed limitation. It is equal to 0.62 Mach when the rotational speed is 2000 revolution per minute.

We will study the 1.4-meter diameter rotor on different ranges:

- Min-Bee's speed: 20 km/h (because they will be used for the vertical flight);
- Rotational speed 500, 1000, 1500, 2000, 2500, 3000 rev/min;
- Altitude: 0, 500, 1000 meters;
- Blade angle: 20, 25, 30 deg.

The rotational speed limitation is due to the tip speed limitation. It is equal to 0.65 Mach when the rotational speed is 3000 revolution per minute.
After defining those range, we quickly decided to increase the speed and altitude range of the 1.4-meter diameter rotor. We decided to use the range of the 2-meter diameter rotor. We want indeed to challenge the fact that we need two-meter diameter rotors.

We first calculated the following coefficient:

$$\frac{\mathrm{V}}{\mathrm{nD}}$$

Where V is the Mini-Bee's velocity (m/s), D is the rotor's diameter (m) and n is the rational speed (rad/s).

It will be used with the following graphics to find the Ct and Cp coefficients corresponding to the blade angle:

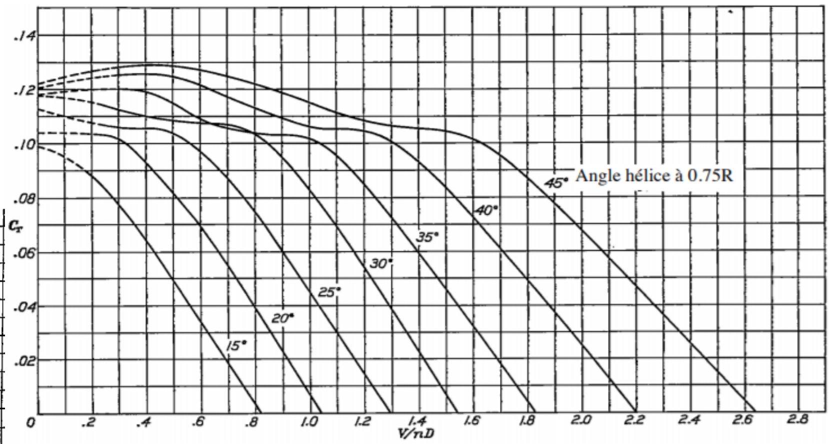


Figure 8 – *Courbes du coefficient de traction pour l'hélice 5868-9, profil Clark Y, 2 pales.*

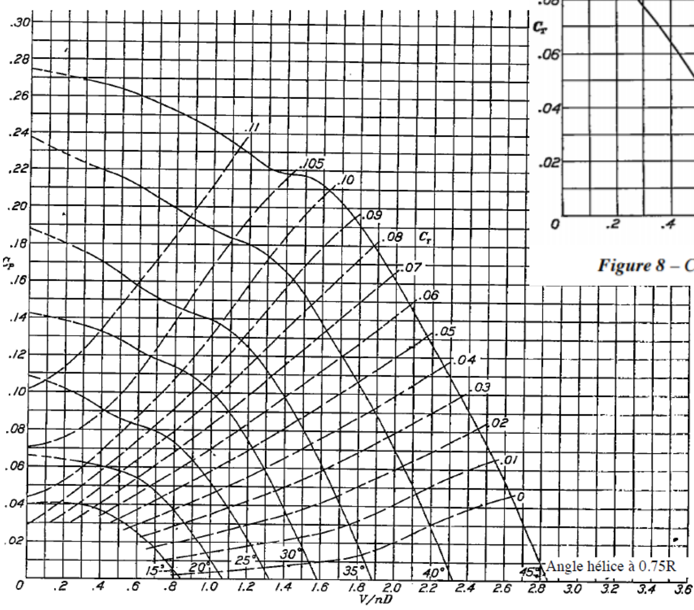


Figure 6 – *Courbes du coefficient de puissance pour l'hélice 5868-9, profil Clark Y, 2 pales.*

We will use the following formulas in order to determine the thrust Te and the Power P:

$$C_T = \frac{T_e}{\rho \cdot N^2 \cdot D^4} \qquad C_P = \frac{P}{\rho \cdot N^3 \cdot D^5} \qquad \eta = \frac{C_T}{C_P} \cdot \frac{V}{N \cdot D}$$

$$C_Q = \frac{Q}{\rho \cdot N^2 \cdot D^5} \qquad C_S = \sqrt[5]{\frac{\rho \cdot V^5}{P \cdot N^2}}$$

Avec :

Te = la traction effective = $T - \Delta D$, N
T = traction sur l'arbre hélice, N
ΔD = variation de la traînée du corps due au souffle, N
P = puissance absorbée par l'hélice, W
N = régime hélice, tr/s
D = diamètre hélice, m
ρ = masse volumique de l'air, kg/m^3
V = vitesse air, m/s
η = rendement propulsif de l'hélice installée
Q = couple moteur Nm.

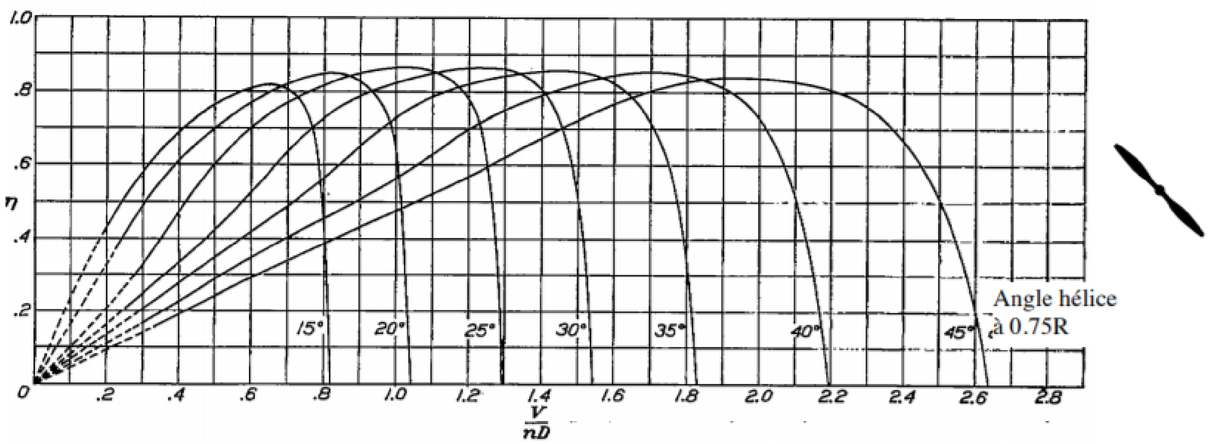


***Figure 5** – Courbes de rendement pour l'hélice 5868-9, profil Clark Y, 2 pales.*

We will then be able to find the needed couple thanks to the equation:

$$P = C * W$$

Where P is the power, C the couple and W the rotational speed.

We also used the graphics mentioned above to determine the rotor's efficiency.

b. Results

We first had to determine the different values of the coefficient $\frac{V}{nD}$. We had to dissociate the two different rotors.

V/nD for a diameter of 1,4m	Rotational speed (rev/min)	500	1000	1500	2000	2500	3000
	Rotational speed (rev/s)	8,33333333	16,6666667	25	33,3333333	41,6666667	50
Mini-Bee's velocity (km/h)	Mini-Bee's velocity (m/s)						
20	5,555555556	0,47619048	0,23809524	0,15873016	0,11904762	0,0952381	0,07936508
50	13,88888889	1,19047619	0,5952381	0,3968254	0,29761905	0,23809524	0,1984127
100	27,77777778	2,38095238	1,19047619	0,79365079	0,5952381	0,47619048	0,3968254
150	41,66666667	3,57142857	1,78571429	1,19047619	0,89285714	0,71428571	0,5952381
200	55,55555556	4,76190476	2,38095238	1,58730159	1,19047619	0,95238095	0,79365079
220	61,11111111	5,23809524	2,61904762	1,74603175	1,30952381	1,04761905	0,87301587

V/nD for a diameter of 2m	Rotational speed (rev/min)	500	1000	1500	2000
	Rotational speed (rev/s)	8,33333333	16,6666667	25	33,3333333
Mini-Bee's velocity (km/h)	Mini-Bee's velocity (m/s)				
20	5,555555556	0,33333333	0,16666667	0,11111111	0,08333333
50	13,88888889	0,83333333	0,41666667	0,27777778	0,20833333
100	27,77777778	1,66666667	0,83333333	0,55555556	0,41666667
150	41,66666667	2,5	1,25	0,83333333	0,625
200	55,55555556	3,33333333	1,66666667	1,11111111	0,83333333
220	61,11111111	3,66666667	1,83333333	1,22222222	0,91666667

We then created tables of Cp and Ct. We associated, to each value of the coefficient $\frac{\mathrm{V}}{\mathrm{nD}}$, a value of Ct and one for Cp. Despite of the work method, the values are accurate and usable.

Ct	Wedging angle (deg)					
V/nD	15	20	25	30	35	40
0,07936508	0,097	0,1035	0,1105	0,118		
0,08333333	0,0965	0,1035	0,1105	0,118	0,119	0,1225
0,0952381	0,096	0,1035	0,11	0,1175		
0,11111111	0,095	0,1034	0,1095	0,117	0,1198	0,123
0,11904762	0,094	0,1034	0,1095	0,117		
0,15873016	0,091	0,1033	0,109	0,1165		
0,16666667	0,09	0,1033	0,109	0,1165	0,11995	0,1235
0,1984127	0,0885	0,104	0,1085	0,1115		
0,20833333	0,0875	0,103	0,108	0,1155	0,12	0,1245
0,23809524	0,085	0,1025	0,108	0,114		
0,27777778	0,08	0,1025	0,1065	0,1135	0,12	0,125
0,29761905	0,0785	0,102	0,1065	0,112		
0,33333333	0,075	0,1	0,106	0,1115	0,1195	0,126
0,3968254	0,065	0,0935	0,106	0,11		
0,41666667	0,0625	0,091	0,106	0,1095	0,1185	0,1265
0,47619048	0,0535	0,086	0,105	0,109		
0,55555556	0,041	0,075	0,101	0,108	0,111	0,1235
0,5952381	0,034	0,07	0,097	0,108		
0,625	0,03	0,066	0,095	0,1075	0,1075	0,1205
0,71428571	0,0175	0,0545	0,088	0,107		
0,79365079	0,0035	0,04	0,0755	0,1035		
0,83333333		0,0345	0,0705	0,1015	0,1035	0,1125
0,87301587		0,029	0,065	0,098	0,1035	0,111
0,89285714		0,0235	0,061	0,096		
0,91666667		0,018	0,0565	0,091	0,103	0,1085
0,95238095		0,015	0,0535	0,0885		
1,04761905		0,0045	0,043	0,081	0,11	0,107
1,11111111		0,0035	0,041	0,08	0,101	0,1065
1,19047619			0,014	0,0545		
1,22222222			0,01	0,0505	0,0835	0,1045
1,25			0,01	0,0505	0,0835	0,1045
1,30952381				0,038	0,0705	0,1
1,58730159						
1,66666667					0,02035	0,0665
1,74603175					0,011	0,0565
1,78571429						
1,83333333						0,0465

We were then able to determine the power, the thrust and the couple needed thanks to the formulas mentioned above.

Thanks to those data, we can determine more precisely the need of the Mini-Bee in term of thrust and couple. Moreover, the figure 5 which gives the efficiency of a rotor in function of the coefficient $\frac{\mathrm{V}}{\mathrm{nD}}$, indicates that the efficiency is very low if the Mini-Bee's velocity is 20 km/h. Indeed, the coefficient $\frac{\mathrm{V}}{\mathrm{nD}}$ is low and it indicates at best a 60 percent efficiency.

That is why we should use a more appropriate blade angle (between 5 and 10 degrees) for the internal rotors which have a diameter of 1.4 meters. The power should be concentrated in those internal rotors for the vertical take-off and landing due to their comparative efficiency. It also involves that we can choose a smaller diameter for the external rotors. Indeed, their diameter was chosen to increase the Mini-Bee's lift. We can use a diameter of 1.4 meters for internal and external rotors. Their price is around 300 euros against 1200 euros for the 2-meter diameter one.

We were also able to determine the appropriate blade angle for the external rotors. We should use an angle of 20 degrees because it is the most efficient in the speed range of the Mini-Bee, and the best compromise for vertical flight on the external rotors. It has to be more precisely determined with the physical rotors in order to be as efficient as possible in cruising flight.

5. Sizing motors

First, we size the external motors in horizontal flight. In this mode, we have 73 Kw available; it is the nominal power of the Rotax 914. We chose the motors' dimensions in the most sizing case of the horizontal flight. This case is when the Mini-Bee has a speed of 220 km/h at null altitude. For these performance we need 240N of thrust per propeller. To find the motor's characteristics, we use the Analysis Excel we made on the rotor.

Entrées	Valeurs
Diamètre de l'hélice (m)	1,4
Choisir altitude (m)	0
Choisir vitesse de rotation (tr/min)	2900
Choisir la vitesse de l'avion (km/h)	220
Choisir l'angle de calage (deg)	20

Sorties	Valeurs
Traction (N)	258,4
Puissance (W)	18226,2
Couple (N.m)	60,0

We chose a blade angle of 20° as explained previously. The four rotors need 72.8 Kw (4*18.2 Kw) to produce the thrust we need in this case. We use four asynchronous motors per rotor (5Kw*4=20Kw). Like that, external rotors can use the exceed power of the Rotax 914 that it can produce for 5 minutes.

Secondly, we know that the external rotors are not adapted for vertical flight. So, we decide to reduce the power on external rotors to concentrate it on internal rotors which are more adapted. We chose the motors' dimensions in the most sizing case of the vertical flight. This case is when the Mini-Bee has a speed of 20 km/h at 1000m of altitude.

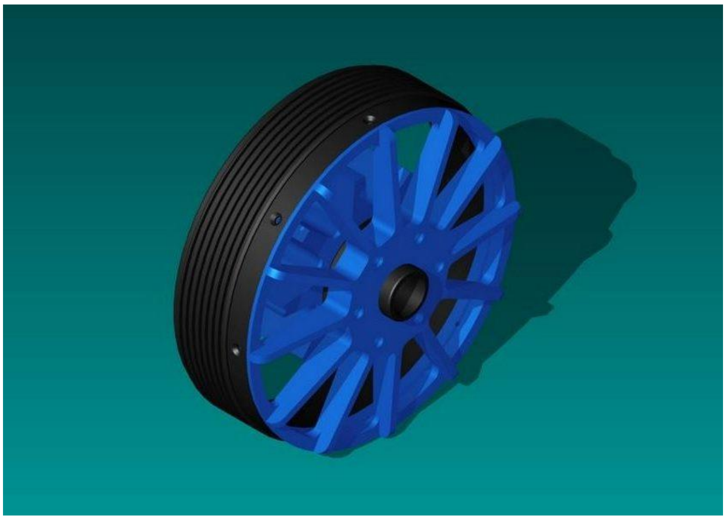
Entrées	Valeurs
Diamètre de l'hélice (m)	1,4
Choisir altitude (m)	1000
Choisir vitesse de rotation (tr/min)	1700
Choisir la vitesse de l'avion (km/h)	20
Choisir l'angle de calage (deg)	20

Sorties	Valeurs
Traction (N)	354,5
Puissance (W)	8907,6
Couple (N.m)	50,0

The four rotors need 35.6 kW (4*8.9 Kw) by continuous current to produce 1418N of thrust (354.4N*4) on the 7000N we need for vertical flight (700*9.8=6860N). The internal rotors have to produce 5582N (7000N-1418N=5582N), so 930N per rotor (5582N/6=930N). We cannot use the Analysis Excel we made for internal rotors, because the blade angle we use is not referenced. So, we use the Excel of the group of last year based on the Momentum theory. To produce 930N per rotor, we need 22.5 kW per rotor. During the vertical flight, we use the maximal power of the Rotax 914. So, each internal rotor uses 14.1 kW of the 85 kW (85 kW/6=14.1 kW) and is equipped with three asynchronous motors (5 kW*3=15 kW).

The rest of the power is supplied by a continuous current motor powered by batteries and the turbine. The total power needed during vertical flight is 170.6 kW (8.9*4+22.5*6=170.6 kW). The internal continuous current motors have a power of 8.4 kW per rotor. It is the same power to supply that for the external rotors. So, we have decided to keep the same continuous current motor on each rotor internal and external. The reference of the motor is Rotex Electic RET 30.

Type	Turn	Voltage (V)	Current continuous / max (kW)	Working rotation	Weight (g)	RPM/V (1)
RET 30	10	120	6 / 15	2500	4100	26



6. Battery choice and sizing

a. Battery type

Before any more research, we must determine the battery type we will use for the Mini-Bee. It will be used to get two boosts of three minutes each. One will be used for the vertical take-off because it consumes too much energy to use only the Turbotech Turbine and the Rotax 914. The other one will be used as a back-up energy in case of a failure of the turbine or the engine.

In this case, the most important data for the battery choice are the energy density and the lifetime. We can also consider the efficiency and the self-discharge of the battery.

Type	Densité massique en Wh/kg	Densité volumique en Wh/L	Tension d'un élément	puissance en pointe(massique) en W/kg	Durée de vie (nombre de recharges)	auto-décharge par mois
Plomb/acide	30-50	75-120	2 V	700	400-1200	5 %
Ni-Cd	45-80	80-150	1,2 V	?	2000	> 20 %
Ni-MH	60-110	220-330	1,2 V	900	1500	> 30 %
Ni-Zn	70-80	120-140	1,65 V	1000	> 1 000	> 20 %
Na-NiCl2 (ZEBRA)	120	180	2,6 V	200	800	->100%(12%/jour)
Pile alcaline	80-160	?	1,5-1,65 V[4]	?	25 à 500	< 0,3 %
Li-ion	150-190	220-330	3,6 V	1500	500-1000	10 %
Li-Po	100-130	?	3,7 V	250	200-300	10 %
Li-PO4 (lithium phosphate)	120-140	190-220	3,2V	800	2000	5%
LMP (lithium metal polymer)	110	110	2,6V	320	?	?
Li-Air	1500-2500	?	3,4 V	200	?	?

According to this table, the batteries with the most interesting energy density are the batteries: Li-ion, Li-Air, Li-PO4 and Li-Po. While considering the lifetime of those batteries, we can choose two types:

- Batterie Li-ion
- Batterie Li-Po4

According to our own research, the Li-ion batteries are mainly used in the aerospace industry mostly due to their energy density. But the Li-Po4 batteries present a big interest in terms of auto-discharge, lifetime but also safety.

Lithium iron phosphate battery	
Specific energy	90–110 Wh/kg (320–400 J/g or kJ/kg)
Energy density	220 Wh/L (790 kJ/L)
Specific power	around 200 W/kg[1]
Energy/consumer-price	3.0–24 Wh/US$[2]
Time durability	> 10 years
Cycle durability	2,000 cycles
Nominal cell voltage	3.2 V

Specific energy	100–265 W·h/kg[1][2] (0.36–0.875 MJ/kg)
Energy density	250–693 W·h/L[3][4] (0.90–2.43 MJ/L)
Specific power	~250-~340 W/kg[1]
Charge/discharge efficiency	80–90%[5]
Energy/consumer-price	3.6 W·h/US$[6]
Self-discharge rate	2% per month[7]
Cycle durability	400–1200 cycles [8]
Nominal cell voltage	NMC 3.6 / 3.85 V, LiFePO4 3.2 V

In practice, the available energy in a lithium ion battery exceed significantly the one available in a Lithium-Po4 battery. We will consequently choose a Lithium-ion battery for the Mini-Bee.

b. Sizing

We need to determine:

- The battery capacity (Ah)
- The maximum/medium/minimum voltage (V)
- The maximum/medium amperage (A)

In order to realize a vertical take-off during 3 minutes with a speed of 20 km/h (in order to reach an altitude of 1000 meters), we need to add 31 kW. We consider that the direct current motor has a 90% efficiency, the battery's efficiency is more than 96% and also that 20% of the energy of the battery is unusable. This energy is sufficient for an emergency landing at a cruising flight altitude or less. The battery will be connected to 10 motors.

This corresponds to an energy of 3.1 kWh because the boost must be delivered twice during 3 minutes each. The battery's capacity depends on the voltage at its terminals. The batteries are mostly sold for a voltage at its terminals of 8V or 28V. We will connect them in series in order to increase the battery's capacity while the voltage stays unchanged.

The battery must deliver 3.63 kWh if we consider the motors' efficiency and the battery's efficiency. Moreover, we must add 20% of capacity for safety. Finally, the battery must have a total capacity of 4.14 kWh.

We choose the battery SLPB125255255[1] and we can consider that the battery will weight 21.36 kg and will include 12 cells and will have a total capacity of 3866.2 Wh.

We have chosen medium capacity cells. We can consider the total weight of the installation is one and a half times the battery's weight. We obtain a final weight of 32 kg.

[1] http://kokam.com/cell/

V. Case of flight

1. Control of the Mini-Bee

The principal source of power of the Mini-Bee is the Rotax 914. The mechanical energy is converted into electrical energy by the Emrax 228, which produces an alternating current for the asynchronous motors. So, the speed of asynchronous motors is controlled by the rotational speed of the Rotax 914. The only device we put in order to control each motor is a switch. To control the Mini-Bee, we have to control the speed of each motor. Thanks to the continuous current motor of each rotor, we can change a little bit the rotational speed by increasing or reducing the power of these motors individually. This motor use electrical power of the batteries or the turbine.

2. Case of failure

Each rotor is motorized by one asynchronous motor and one continuous current motor. If one motor fails, this configuration allows that each rotor can continue to rotate. Moreover, we have chosen the turbine of Turbotech to produce a part of the continuous current and not a full battery configuration. Like that we have continuous current as long as there is fuel, and it is still a big source of power if the Rotax fails.

3. Flight case

We studied two different flight cases at 190 km/h and 200 km/h. For both cases, we will consider two types of flight: at null altitude and at an altitude of 4000 meters.

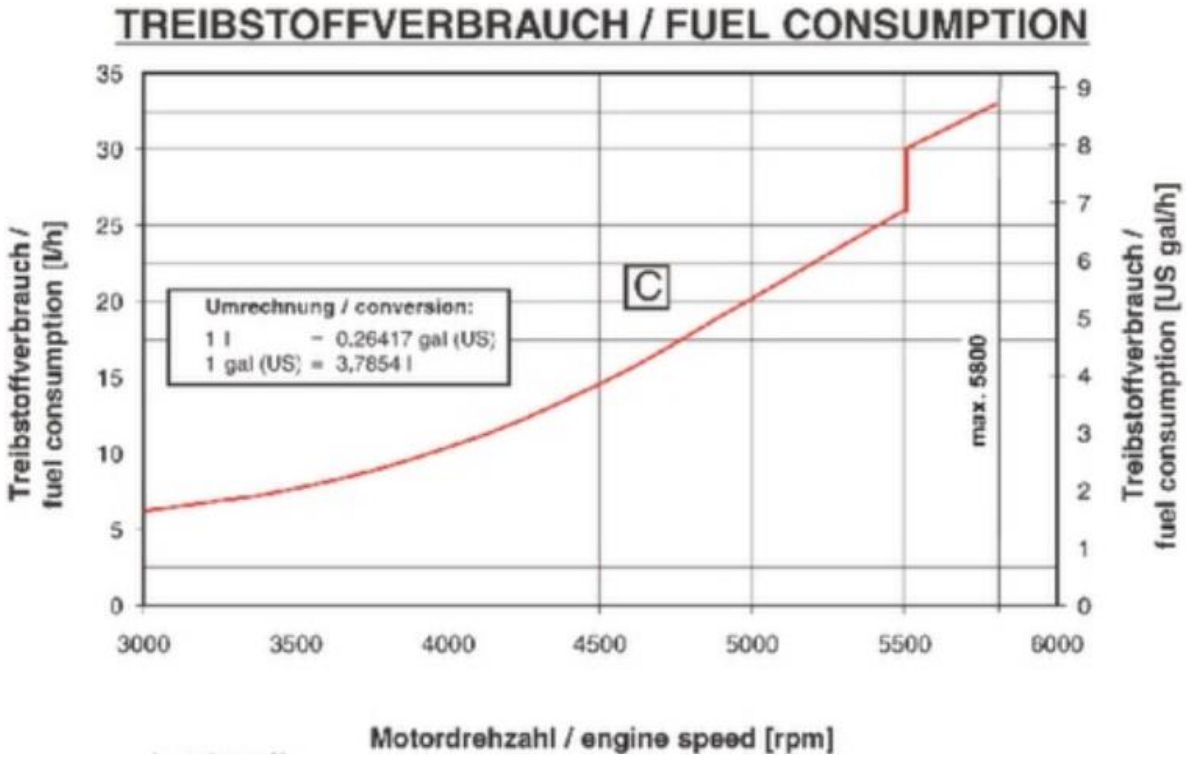
First at 190 km/h:

- At null altitude, one external rotor, with a rotational speed of 2500 RPM, can provide a thrust of 192 N and a power of 11.7 kW. Therefore, our four rotors provide 46.8 kW.
- At the altitude of 4000 meters, one external, with a rotational speed of 2500 RPM, rotor can provide a thrust of 120 N and a power of 7,9 kW. Therefore, our four rotors provide 31.6 kW. Here, we need the internal rotors to provide 103 N and 2.7 kW.

Then at 200 km/h:

- At null altitude, one external rotor, with a rotational speed of 2600 RPM, can provide a thrust of 207 N and a power of 13.7 kW. Therefore, our four rotors provide 54.6 kW.
- At the altitude of 4000 meters, one external rotor, with a rotational speed of 2500 RPM, can provide a thrust of 133 N and a power of 9,1 kW. Therefore, our four rotors provide 36.5 kW.

Those data will allow us to determine the flying range and the consumption of our Mini-Bee. We will calculate those parameters at the altitude of 3000 meters and at several speed: 220 km/h, 200 km/h and 190 km/h. We will use those data:



Our fuel tank contains 90 Liters of fuel. 50 liters of them will be used in cruise flight and the remaining 40 liters must be used for the takeoff and landing and can also be used in tough circumstances.

At the speed of 220 km/h, the Rotax 914 provide a power of 54 kW with a rotational speed of 4200 RPM. It corresponds to a fuel consumption of 10 L/h. It represents a range flight 1100 km.
At the speed of 200 km/h, the Rotax 914 provide a power of 41 kW with a rotational speed of 3500 RPM. It corresponds to a fuel consumption of 8 L/h. It represents a range flight 1250 km.

At the speed of 190 km/h, the Rotax 914 provide a power of 35 kW with a rotational speed of 3200 RPM. It corresponds to a fuel consumption of 6 L/h. It represents a range flight 1580 km.

4. Minimum speed

We need to estimate the minimum speed for which the internal rotors become useless. We need to evaluate that speed for different altitudes:

- 1000m: 172 km/h
- 2000m: 180 km/h
- 3000m: 190 km/h
- 4000m: 200 km/h

5. Building step of the prototype

The prototype of the Mini-Bee will be built step by step to test different systems and validate technical solutions. In this part we focus on the different test versions of the demonstrator.

- Step 1:

Equipments: 6*RET 30, 6*ESC, 6*Propeller 1.4m, 55Kw of batteries
MTOW: 300 kg

The vertical flight will be tested with only the intern continuous current motors of Rotex electric. Each motor produces a power of 9 kW and the demonstrator needs 55 kW supplied with batteries. It is controlled from the ground like a drone. The flight lasts 3 minutes like a boost.

- Step 2:

Equipments: 6*RET 30, 6*ESC, 6*Propeller 1.4m, 55 kW of batteries, Rotax 914, Emrax 228, 6*assembly of three asynchronous motors, 18*SSR
MTOW: 540 kg

The vertical flight will be tested with the intern continuous current motors and asynchronous motors. The Rotax supplies alternative current and we keep the 55 kW delivered by the batteries. It is still controlled from the ground like a drone. The flight lasts 3 minutes like a boost.

- Step 3:

Equipments: 10*RET 30, 10*ESC, 10*Propeller 1.4m, 55Kw of batteries, Rotax 914, Emrax 228, 6*assembly of three asynchronous motors, 4*assembly of four asynchronous motors, 34*SSR, 4*tilt motor.
MTOW: 700 kg

The horizontal flight will be tested with the external and internal continuous and asynchronous current motors. The Rotax delivers alternative current and we use the power of 55 kW delivered by the batteries. Tilt motors are also tested in order to check the control of the Mini-Bee's directions. Thanks to the internal rotors the Mini-Bee can fly at low speeds. It can be controlled by a pilot.

- Step 4:

Equipments: 10*RET 30, 10*ESC, 10*Propeller 1.4m, 31Kw of batteries, Rotax 914, Emrax 228, 6*assembly of three asynchronous motors, 4*assembly of four asynchronous motors, 34*SSR, 4*tilt motor, turbine
MTOW: 700Kg

The Mini-Bee can fly in all the modes with a pilot. It is the final version.

VI. Maximum speed case: (Vmax=265 km/h)

Using our excel calculation sheet, we found out that the mini-Bee can fly up to 265km/h for an altitude of 4000m. This maximum speed cannot be reached for an altitude below 4000m because there is too much drag for such altitude. Moreover, the Rotax 914 cannot power more than 85 kW and we are not using the batteries and the turbine in cruise flight.

We can finally estimate the mass and cost balance:

Mass and cost balance				
Component	Number	Mass/unit	Mass (kg)	Price (€)
Rotax	1	74,7	74,7	30000
Emrax	1	12,3	12,3	2800
Turbine	1	50	50	50000
Batteries	1	32	32	5000
Asynchronous motors	34	2	68	NA
Brushless motors	10	4,1	41	61200
Rotor	10	1	10	3000
Tilt motors	4	1	4	400
Fuel (L)	90	0,8	72	NA
ESC	10	0,3	3	10000
TOTAL			367,0	162 400,00 €

The MTOW of the Mini-Bee cannot exceed 700 kg. The propulsion system is already boosted with the batteries. The demonstrator's MTOW is the same as the initial hypothesis of 700 kg which is half of the final version's weight.

Concerning the price, we cannot add the asynchronous motors because they are not already designed. They will be 3D-printed in aluminum. The total cost of our solution exceeds a bit the first hypothesis: 162 k€ against 150 k€.

VII. Conclusion

This Mini-Bee's demonstrator is built around the use of the Rotax 914 as the main power source, with the combination of continuous and alternating current. The aim of this ambitious configuration is to limit the price and the mass by replacing continuous current technologies by alternating current technologies. To do that, each rotor is equipped with an assembly of several asynchronous motors and one brushless motor. The asynchronous motor developed could also equip the final version of the Mini-Bee. They are designed for a 1.4-meter diameter rotor and can be assembled if we need more power. The continuous current motors allow the control of the flight's directions and the boost during the vertical flight. The continuous current is produced by the turbine and batteries as for the final version. The Mini-Bee demonstrator can fly vertically like a helicopter during 3 minutes with an upward velocity of 20 km/h and horizontally with a cruise speed exceeding 200 km/h and with a maximal speed of 265 km/h.

We recommend that the next project group work on the structure of the Mini-Bee to calculate values more precisely (frontal area, lift coefficient, etc.). Indeed, all calculations have been done with hypothesis. Moreover the transitional flight mode (between vertical and horizontal flight) should be analyzed with an aerodynamic structure group and a propulsion group which could work on the tilt motors.

Appendixes

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https://emrax.com/products/emrax-228/

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