DEVELOPMENT OF THE REGENERATIVE SOARER: THEORETICAL AND PRACTICAL ASPECTS

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Keywords: *regenerative flight, sailplane, electric propulsion, energy harvesting*

Abstract

The regenerative soarer is an aircraft capable of flying by harvesting energy from atmospheric updrafts and storing it in an energy accumulator, thus differing to the conventional sailplane, which acquires energy in the form of geopotential height.

That aircraft features one or more windmill driven electrical generators which recharge a bank of batteries and this stored energy allows the execution of flight segments through the electrical motor(s), until the aircraft can acquire another chunk of energy, depending on the flight strategy.

By using mathematical analysis, real-world flight data and his own flight experience, the author intends to define a simplified typical mission profile, establish an aircraft configuration, perform initial sizing of key system components and calculate theoretical system performance for the mission task, aiming at convincing sailplane designers that such a machine is currently possible.

1 Introduction

Soaring flight is an evolving activity since the dawn of aviation, as it can be evidenced by the pleasuring reading of reference [1], also [2], [3].
Soaring has come through many technical stages/improvements, like the initial evolution from the short hopes of the first primitive training gliders to cross-country flying as performed by modern high-performance machines.
The evolution of gliders design went from the first kite inspired gliders to the adoption of high aspect ratio wings and more aerodynamically refined airframes, the evolution of materials, the integration of the flight activity with the information technology tools and more recently, the dissemination of the self-launching sailplanes.
The author considers that despite its enormous evolution, sailplane development has reached a design barrier, because recent performance improvements have been obtained by the adoption of increasingly higher wing loading and aspect ratios, aiming at achieving higher cross-country speeds. So, sailplane designers have been hindered by the classical conflict of design objectives that arises when an increase in wing loading causes higher gliding speed but also causes higher sink rate during circling in thermals. Since the design trend of increasing the wing aspect ratio has been explored to its practical limitations, it is not wise to expect further performance improvements by following this path, as is discussed in [4].
Other disadvantages of that design strategy are:

- Sailplanes with high wingspans are heavy difficult to handle on the ground;
- Heavy sailplanes require a capable tow plane for launching, what adds to operation costs. When self-launching, the engine installation must be powerful enough to safely perform this critical phase of flight;
- A high wingspan with high weight requires structures employing expensive high-tech materials.

Considering this scenario, and for the sake of pursuing innovation, the author has dedicated some effort in recent years to the investigation of the regenerative soarer, which is an aircraft with the same objective as the conventional sailplane: flying by using only the energy obtained from

atmosphere updrafts. It differs from the latter in the aspect that instead of being limited to using air updrafts to gain height and then fly a glide segment to the next thermal, it can also convert energy acquired from the atmosphere into electrical energy, which is stored in an accumulator for subsequent use when flying cruise segments.
At first, the latter approach seems to be prohibitively inefficient due to the conversion of mechanical energy into electrical energy, storage, recovery and conversion to mechanical energy again, with all associated losses. That was the author's belief for some time, before considering other aspects which have a profound influence on the overall aircraft task performance. These aspects will be discussed ahead.

2 Historical aspects

The idea of such an aircraft is not new but, although a few authors have dealt with it, the topic has not evolved considerably.
The author considers the regenerative soarer idea began as a paper by Paul Mc Cready [5]. There he explains the principles of converting atmospheric updrafts energy into electrical energy and later making use of it to gain height, albeit with some inefficiency. He did not seem to consider the option of utilizing the electrical energy to fly at the same altitude and taking credit of a high airspeed cruise optimized airframe, instead of climbing and then gliding.
Another author who remains enthusiast of the idea is J. Philip Barnes. In his works [6] and [7] he proposes using an airscrew which is both a propeller and a windmill and advocates its feasibility with a mathematically elegant theory.
There are equally works presenting control algorithms for UAV´s which take advantage of atmospheric updrafts for range or endurance increase.
Regarding regenerative flight aircraft, a search in the internet unearthed a few light electric aircraft which are capable of regenerating energy by operating the propeller in its "windmill" regime albeit at low windmilling efficiency [8], [9].
The advent of the electric vehicle era has improved the batteries, motors, and power converters, with focus on ground vehicles but also lightweight general aviation. All this have high potential to allow another vehicle to come to life: the regenerative, electrically powered sailplane.

3 Flight Profiles: The Conventional x Regenerative Sailplane

This work is based on simplified mathematical flight models for both the conventional and regenerative sailplanes. Those will make it possible to compare both solutions in terms of the more relevant parameters.

3.1 Flight Model: Classical Sailplane

In a simplified view, the conventional sailplane will circle inside a thermal to acquire energy in the form of geopotential height and will fly to the next available thermal, as shown in Fig 1. This cycle will be continued until its intended destination is reached.

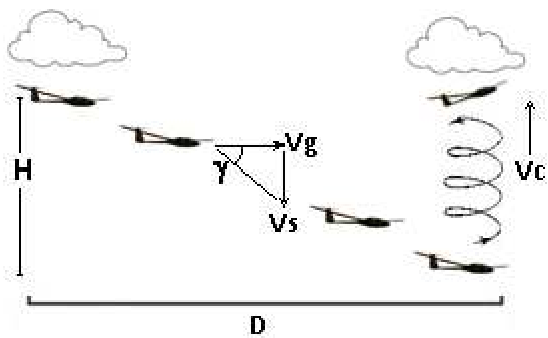


Fig 1. Conventional Soaring Flight Cycle

The mean cross country speed V_{avg} can be defined, as done in [4], by the following relations:

$$V_{avg} = \frac{D}{t} \quad (1)$$

$$t_c = \frac{H}{V_c} \quad (2)$$

$$t_g = \frac{H}{V_s} \quad (3)$$

$$t = t_c + t_g \quad (4)$$

$$D = \frac{V_g}{V_s} * H \qquad (5)$$

$$V_{avg} = V_g * \frac{V_c}{(V_c + V_s)} \qquad (6)$$

So, for the conventional sailplane, the cross country speed was defined in terms of its climb speed V_c in the thermal, its sink speed and airspeed V_g in glide.

3.2 Flight Model: Regenerative Sailplane

For the regenerative sailplane, the flight cycle is shown in Fig 2.

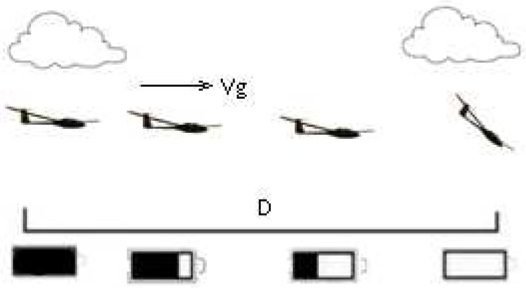


Fig 2. Regenerative Soaring Flight Cycle

It begins at a specific height with a stored amount of energy and proceeds in level flight to the next thermal. Upon reaching it, it circles at the same height instead of climbing and uses the updraft's excess vertical speed to propel a windmill to recharge its energy storage.
As for the conventional sailplane, an average cross country speed can be defined here but now we have to think in terms of energy instead of the trajectory. By considering that the energy spent during the cruise is the same that must be regained while circling in the next thermal, we can write the following relations:

$$V_{avg} = \frac{D}{(t_g + t_c)} = \frac{V_g * t_g}{(t_g + t_c)} \qquad (7)$$

If we consider the amount of energy used to travel the distance D and designate it E, then

$$E = P_g * t_g = P_c * t_c \qquad (8)$$

In (8), P_g represents the power required for cruising at V_g and P_c represents the power obtained while circling in the thermal.
From relation (8), we can write:

$$t_c = \frac{P_g * t_g}{P_c} \qquad (9)$$

$$V_{avg} = \frac{V_g * t_g}{\left(t_g + \frac{P_g * t_g}{P_c}\right)} = \frac{V_g}{\left(1 + \frac{P_g}{P_c}\right)}$$

$$V_{avg} = V_g * \frac{P_c}{(P_c + P_g)} \qquad (10)$$

3.3 Comparing flight models

The equation (6) can be developed into equation (10). The term V_c can be written as a function of the mean power absorbed by the conventional sailplane while climbing in the thermal:

$$V_c = \frac{P_c}{m * g} \qquad (11)$$

Likewise, V_s also can be written as a function of the mean power spent while gliding from one thermal to the next:

$$V_s = \frac{P_g}{m * g} \qquad (12)$$

Substituting V_c and V_s in (6):

$$V_{avg} = V_g * \frac{V_c}{(V_c + V_s)} =$$

$$V_g * \frac{\frac{P_c}{m * g}}{\left(\frac{P_c}{m * g} + \frac{P_g}{m * g}\right)} =$$

$$V_{avg} = V_g * \frac{P_c}{(P_c + P_g)}$$

So, the same expression applies to both flight profiles.
Qualitatively, we can see that for both sailplanes, V_{avg} increases with the power possible to absorb from the thermal and decreases with the power spent to fly to the next thermal.

For the conventional sailplane, the first term, P_c, is favored by low wing loading and high maximum possible C_l. For the regenerative sailplane, however, the author considers a good strategy maximizing the drag margin available (how much parasitic drag can be added to the airframe before the climb speed goes to zero). That happens because the drag margin makes it possible to drive a windmill to generate electrical energy.

Regarding P_g, it should be as small as possible for both conventional and regenerative sailplanes. It will define the glide path angle for the first and the energy storage discharge rate for the later.

At this point, it is worth exploring a bit more the current design trend of increasing the wing loading for conventional sailplanes. As said earlier, current sailplane designers rely on increasing wing loading for reaching higher values of Vg. The rationale behind that is the fact that the sailplane's weight component in the same direction as V_g is the force that balances the drag, as shown in Fig 3.

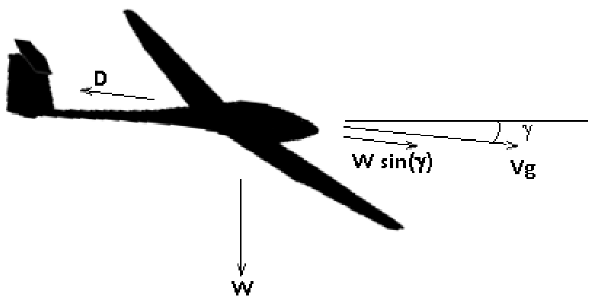


Fig 3. Gliding Flight Equilibrium

From the figure, the following relation can be drawn:

$$D - W\sin(\gamma) = 0$$

or

$$\sin(\gamma) = -\frac{D}{W} \qquad (13)$$

In relation (13), increasing the weight without increasing wing area (i.e. increasing *W/S*) will maintain the equilibrium but at a higher airspeed, because we must have a higher lift to balance the increased weight with the same wing area.

This new equilibrium situation comes at a cost: the value of P_g in (12) will increase as well.

The energy consumption in a glide is not clearly apparent for conventional soaring but that is the cost to be paid when trying to climb in the next thermal. This fact represents the designer´s “wing loading dilemma”.

In the case of the regenerative sailplane, the force that balances the drag in cruise is not a component of weight because the flight is in level, and the drag must be balanced by the propeller´s thrust. As done in [10], we can derive the value of P_g for steady level flight:

$$D = D\frac{W}{L} = W\frac{C_d}{C_l}$$

$$V_g = \sqrt{\frac{2W}{\rho S C_l}}$$

$$P_g = DV_g = W\frac{C_d}{C_l}\sqrt{\frac{2W}{\rho S C_l}}$$

$$P_g = W\frac{C_d}{C_l^{\frac{3}{2}}}\sqrt{\frac{2}{\rho}}\sqrt{\frac{W}{S}} \qquad (14)$$

From equation (14) it can be seen that Pg decreases with lower wing loading and as result, the “wing loading dilemma” does not affect the regenerative sailplane. So, diminishing the wing loading will benefit both cruising and circling in thermals.

Nevertheless, the regenerative sailplane will exhibit another design conflict to be explained below.

If we consider the sailplane aerodynamic sinking during circling, it can be expressed in terms of flight and airframe parameters as shown in equation (15), taken from [11]:

$$\dot{z} = \sqrt{\frac{W}{S}}\sqrt{\frac{2}{\rho}}\frac{C_d}{\left[{C_d}^2 + (C_l\cos\beta)^2\right]^{3/4}} \qquad (15)$$

So, if V_t is the updraft vertical velocity, the sailplane climb speed relative to ground is equal to:

$$V_c = V_t - \dot{z} \qquad (16)$$

The power absorbed by the vehicle while flying in the updraft is equal to:

$$P_c = V_c * W \qquad (17)$$

$$P_c = W * \left(V_t - \sqrt{\frac{W}{S}} \sqrt{\frac{2}{\rho}} \frac{C_d}{\left[C_d{}^2 + (C_l \cos\beta)^2 \right]^{3/4}} \right) \qquad (18)$$

The equation (18) shows the value $W*V_t$ represents the asymptotic limit for P_c when diminishing the value of *W/S*. So, the designer would like to obtain the most diminished possible value of *W/S* for both circling and cruising but he/she would need a high value of *W* for circling and a low value of *W* for cruising in order to get high P_c and a low P_g.

Since a change in *W/S* will probably cause a change in C_d and C_l for whatever reasons, the optimization of P_c does not depend exclusively on *W/S*.

So, how to optimize the regenerative sailplane airframe for best performance? This is a topic for future work, and the author hasn´t yet fully developed his ideas.

3.4 Conventional x Regenerative Soaring: Pros and Cons

There are various aspects that favor one or other soarer. These aspects can be divided into design aspects, flight scenarios, and flight strategies. Each aspect will be discussed ahead.

3.4.1 Design aspects

When comparing the regenerative and conventional sailplanes considering only design, are noteworthy the aspects in Table 1.

Aspect	**Conventional**	**Regenerative**
Efficiency	The classical sailplane is an extremely efficient machine due to already well-established engineering and construction techniques.	The aircraft, when optimized for its task, lacks efficiency at gaining height and the energy conversion to electricity is less efficient than geopotential energy acquisition.
Conflicts in design objectives	There is a marked conflict of objectives when choosing the wing loading for flying in thermals and in glide.	Due to the diverse form of acquiring energy from the atmosphere, both the flight in thermals and cruise flight are favored by a low wing loading, what breaks the design conflict.
Cost	The high-tech modern sailplane is an extremely costly vehicle and there is no perspective for cost reduction.	The purpose-designed regenerative sailplane is probably smaller, lighter, less sophisticated airframe of lower manufacturing cost. It features an onboard electrical/regen system of initial high costs but which tends to be cheaper with time and scale.
Self-launching capacity	Self-launching capacity comes at a significant increase on basic sailplane price.	Self-launching capacity uses inherent vehicle propulsion at a penalty in cross country performance due to increased battery weight and bigger motor.
Ground handling	The conventional sailplane is heavy and difficult to handle on the ground and inside the hangar.	The optimally designed regenerative sailplane is a light vehicle, much easier to deal with on the ground.
Innovative features	Current improvements in high-performance sailplanes are only small steps on the already explored path with no innovation on aircraft or flight techniques.	The regenerative sailplane focus on emergent technologies with the potential to drive radical changes in aircraft design and flight techniques.
Maintenance	A typical club sailplane is a machine that demands simple maintenance and inspections. The high-performance sailplanes demand a more maintenance but much less than general aviation aircraft.	The regenerative sailplane will include a considerably complex power/regen system featuring one or more propellers/windmills. That system will require maintenance and inspections.
Fitting to current technology trends	Classical soaring has been stuck in a design barrier for a considerable time and no disruptive technology has emerged recently.	The regenerative sailplane is a research that fits neatly into current technology trends when electrically powered vehicles are being pursued.

Table 1 Pros and Cons of conventional and regenerative soaring

3.4.2 Flight Strategies and flight scenarios

The classical sailplane is an extremely efficient machine whose design makes it capable of climbing with high energy efficiency.

The regenerative soarer, on the other hand, is not optimized to gain height but to convert the updrafts energy into electrical energy and some flight scenarios that are bad for the conventional sailplane can be circumvented or even used to advantage.

The following items are a discussion of these scenarios and are yet to be explored by pilots, when an adequate flight vehicle is available.

3.4.2.1 Ridge soaring

When flying in ridges, the classical glider is limited to the maximum height of the orographic updraft to obtain lift. Therefore, it may be not possible to evolve the flight task if no promising scenarios are nearby. The regenerative sailplane can fly up and down alongside the ridgeline, until it converts enough energy to proceed in the navigation task, as illustrated in Fig 4.

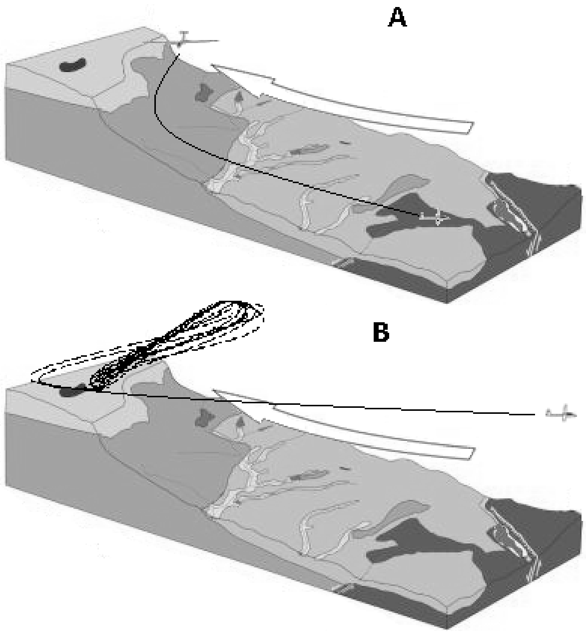


Fig 4. Ridge Soaring: (A) Conventional, (B) Regenerative.

3.4.2.2 Low cloud base

When flying under low cloud base, the conventional sailplane does not have a good height reserve to cross "weaker" soaring areas. The regenerative sailplane although can collect energy at cloud base until being able to venture into another promising area, as shown in Fig 5.

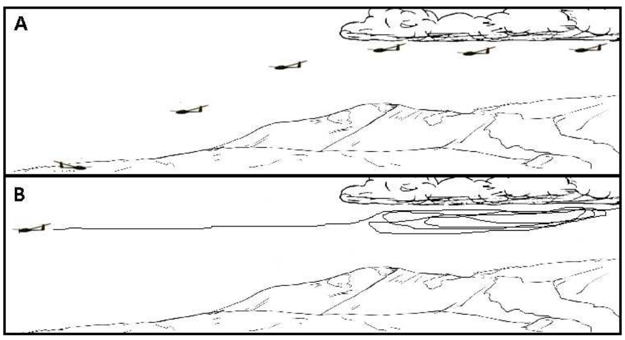


Fig 5. Low ceiling: (A) Conventional, (B) Regenerative.

3.4.2.3 Height for best thermal strength

When climbing in thermals it is possible to notice the thermal strength varies with height and the best strength is not at the top, as shown in Fig 6, taken from [12].
The conventional sailplane cannot afford to stay inside the best updraft region but the regenerative sailplane can choose the most convenient height to fly in order to maximize updraft energy absorption because of horizontal its flight path.

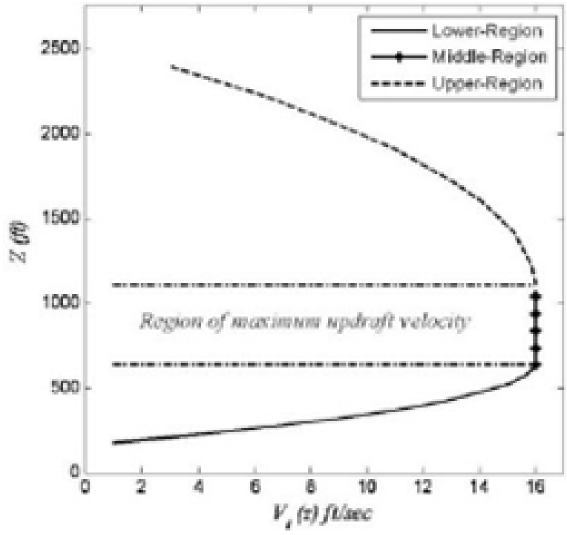


Fig 6. Updraft Strength Profile, from [12]

3.4.2.4 Climb to reach thermals

The regenerative soarer embraces the possibility of actually climbing in still air, and this offers the possibility of reaching thermal vortex shells (as described in [11]) which are inaccessible to the classical sailplane.

3.4.2.5 Radius of turn in thermals

Thermals come in various flavors, as described in [4] and the modern high-performance sailplane is a high span machine not well suited for turning inside narrow thermals or in the core of strong thermals. An optimized regenerative sailplane has lower wing loading and will be able to make turns of a shorter radius, what makes it more capable of taking advantage of narrow thermals, as discussed in [14].

4 Feasibility Study for the Regenerative Sailplane

The main aspect of this work is a regenerative flight feasibility study that takes the recorded

data from 36 real-world flights executed in Europe and calculates the performance of a regenerative sailplane for the same flight tasks.
The feasibility study is available at https://drive.google.com/drive/folders/1efjuOrDCPwLjmk_eNDYxksky9DX0_9tk?usp=sharing. Newer versions will be posted when available.

4.1 Flights Selected for the Study

The 36 flights for this study were selected from [15] and involved single place sailplanes with no advanced features like flaps or engine and whose stored flight data contained the data from GPS and also from anemometric speed indication.

4.2 The Regenerative Sailplane

For the feasibility study, it was decided to take one existing sailplane and having in mind what is discussed in item 3.3, the APIS PG (pure glider) [16] was selected based on its speed polar.
It is shown in 7, after adding the necessary components to become a regenerative sailplane:

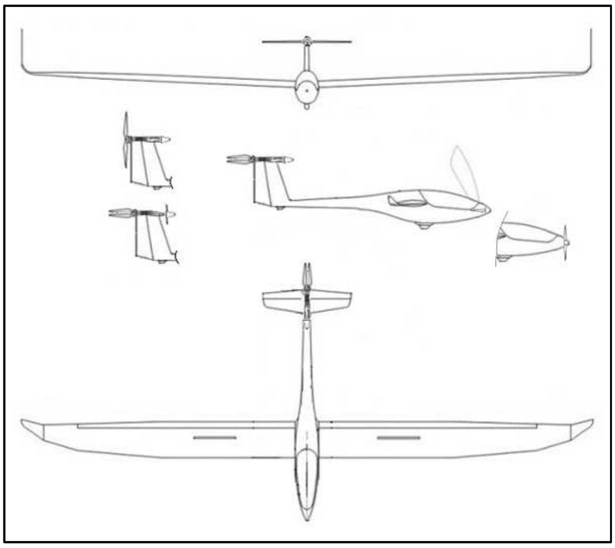


Fig 7. Regenerative aircraft based on the APIS sailplane

4.3 Propulsive/Regenerative System Concept

The regenerative sailplane features a propulsive/regenerative electrical system responsible for energy acquisition, conversion, storage, and recovery.
Fig 8 shows a system simplified view.

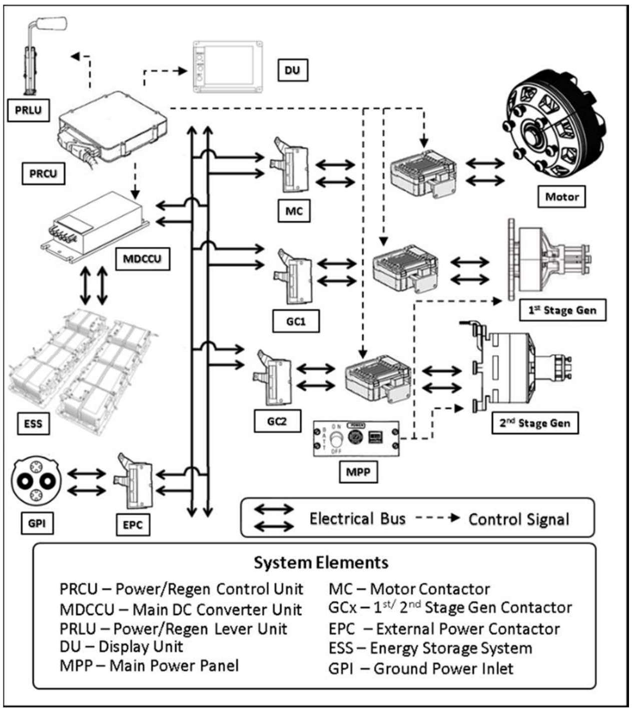


Fig 8. Propulsive/Regenerative System Overview

Only the main system elements are shown in the overview. No discussion on the system details will be done here due to space restrictions.

5 A mathematical tool: The Regenerative Flight Feasibility Study

In order to carry out an off-line, steady state, simulation of the regenerative sailplane's flight, a MS Excel spreadsheet was built.
In this study the flight segments were "recalculated" by substituting the original sailplane performance characteristics by the performance characteristics of the regenerative sailplane while operating the propulsive/regenerative system at the same meteorological conditions originally flown.
A comprehensive description of the simulation implementation in the spreadsheet would be very lengthy and was omitted. Relevant aspects although are the mathematical model of the energy storage which built as Visual Basic functions based on charging and discharging curves taken from [22], [23], [24], [25], [26] and the mathematical model of the propellers and windmills which were provided by the software JavaProp [27], integrated to the spreadsheet.
There are no detailed mathematical models of the electrical motors and generators and typical

values of efficiency were used, until further improvements are done.
In relation to airspeed, two flight strategies were pursued in the simulation, as described below, and their results are compared in item 7.

5.1 Cruise/glide flight at the same airspeed as the classical sailplane

In this simulated flight strategy, the regenerative sailplane tried to execute the same tasks as the classical sailplanes for each flight at the same flown airspeeds but not necessarily at the same altitude.

5.2 Cruise flight at best L/D speed

In this simulated flight strategy, the regenerative sailplane executes the thermal circlings in the same way as performed by the conventional sailplane but performs the cruise segments at the best L/D speed (95 km/h), in order to save energy, or the minimum airspeed necessary for a ground speed higher than 10 km/h. This flight strategy increases the probability of completing the simulated task due to higher time interacting with updrafts and consequent higher energy availability.

6 Propulsive / Regenerative System Aerodynamic Components Sizing

Since the regenerative sailplane is an aircraft whose cross-country performance is better with lower wing loading, the sizing of the various propulsive/regenerative system elements is critical for the aircraft performance. Oversized motors will waste energy through excess internal friction, excess weight, and by running outside the better efficiency operating condition. The number of on-board batteries must be adequate for the meteorological conditions and airframe efficiency, otherwise the vehicle will not be able to take credit of all atmospheric energy available or, in case of excess of batteries, will just be taking some dead weight for a ride. The strategy for the dimensioning of the main system elements is described below.

6.1 Propeller Sizing

For minimizing the drag when not in use, the propeller is to be foldable and it will feature a variable pitch mechanism for efficiency. It's performance chart is shown in Fig 9.

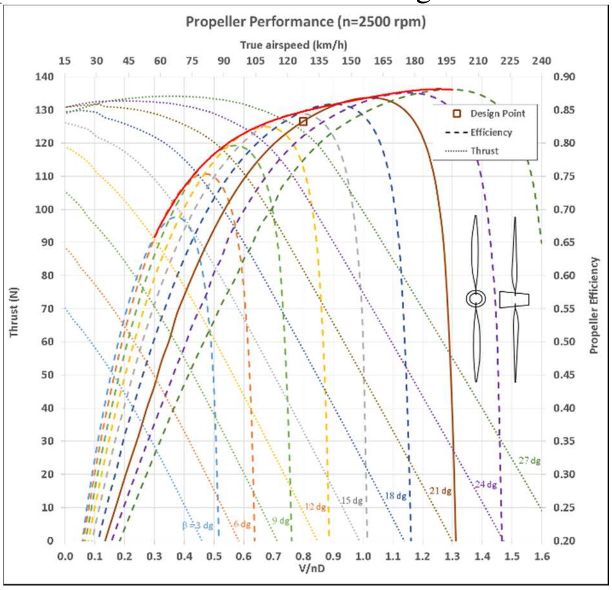


Fig 9. Propeller performance chart

The required thrust for flying cruise segments is shown in Fig 10 and airspeeds in Fig 11.

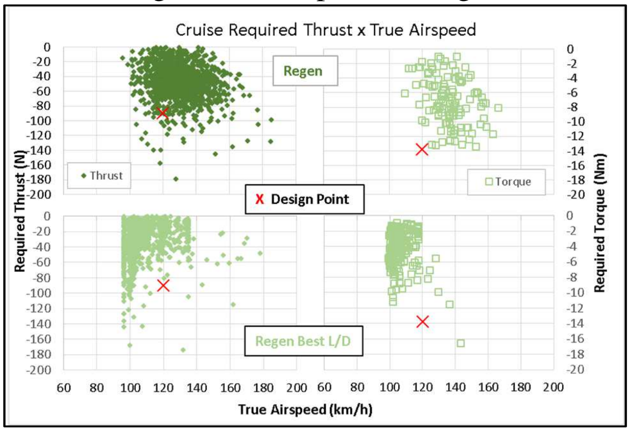


Fig 10. Propeller thrust and torque for all cruise segments

Based on the data shown, it was decided to size the propeller for providing 90 N at 120 km/h.

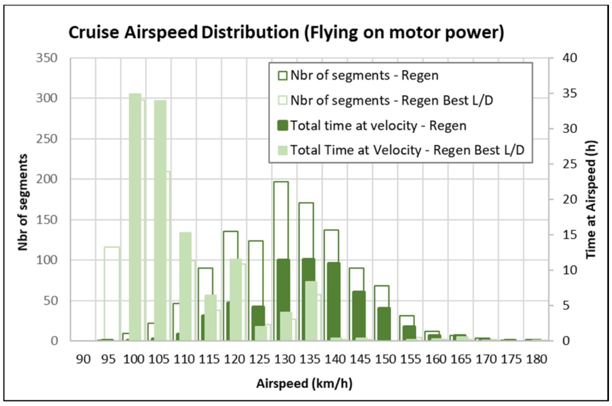


Fig 11. Airspeed distribution for cruise

6.2 Windmills Sizing

Fig 12 is the performance chart for the windmills.

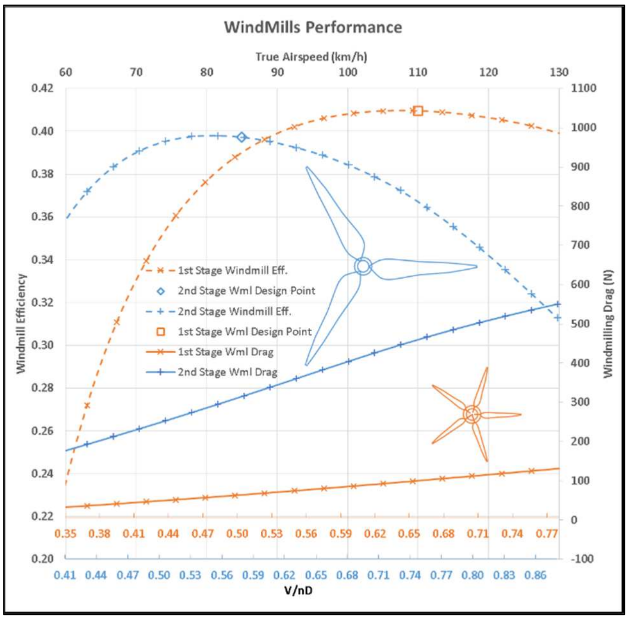


Fig 12. Windmills Performance Chart

The sizing of the windmills was done in a similar way as for the propeller. The author decided to have two windmills, one smaller, called 1st stage windmill and a second, larger, called the 2nd stage windmill and they do not operate simultaneously. Fig 13 is an airspeed histogram for the flight segments when flying in updrafts. It is possible to see that for the "Regen" strategy the vehicle would benefit from a windmill optimized for operation around 75 km/h. For the "Regen at Best L/D" strategy the drag margin is spread between 75 and 120 km/h.

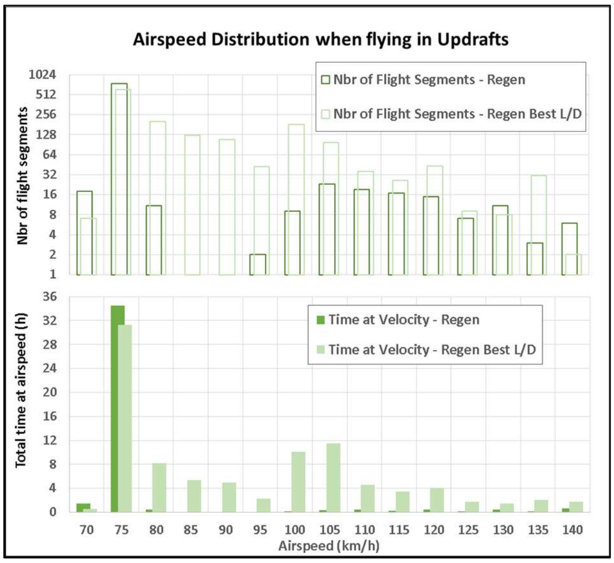


Fig 13. Energy regeneration flight segments distribution for airspeed

In order to size the windmills diameter, a plot of windmilling drag margin against airspeed is useful, as shown in Fig 14.

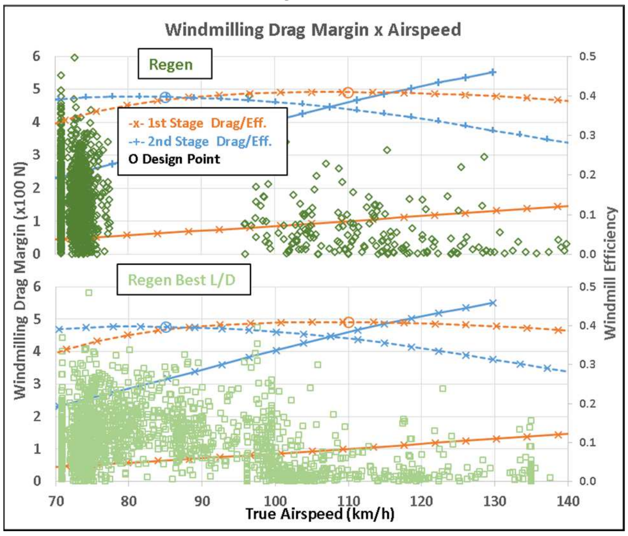


Fig 14. Windmilling Drag Margin

The 1st stage windmill was designed targeting a windmilling drag of 100 N at 110 km/h and is suitable to take advantage of the drag margin at higher speeds, from 90 to 130 km/h. It has a diameter of 0.56 m and a high rotational speed of 5000 rpm and features 5 blades for higher efficiency and lower noise.

The 2nd stage windmill is 3 bladed, diameter of 1.3 m, turning at 1900 rpm, optimized for best efficiency at 85 km/h with a drag of 300 N, well suited for low speed segments and circlings.

6.3 Energy Storage Sizing

The energy storage system must be capable of absorbing the net energy available when any of the windmills is used and providing the gross power for cruising on electric motor power.

It is composed by an arrangement of Lithium Iron Phosphate battery cells in series and in parallel groups calculated automatically by a simple algorithm whose inputs are the desired system voltage, energy capacity and power capacity. The latter two parameters can be obtained from a plot of the energy margin, show in Fig 15.

By looking at the plots, the energy capacity of 1.0 Mj and the Power capacity of 4.0 kW cover the demands represented by the red dots.

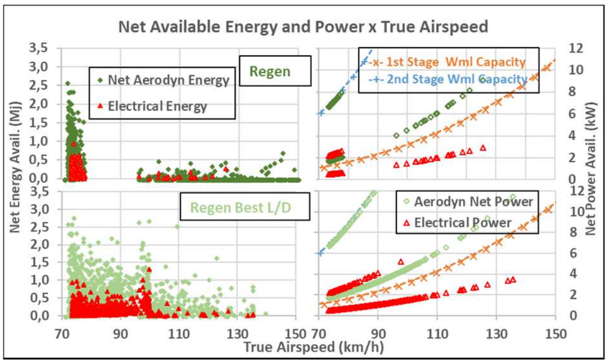


Fig 15. Net Energy Available for Regeneration in Cruise

The resulting battery association is shown in Table 2.

Battery Arrangement	
Target Energy (kWh):	1,0
Target Power (kW):	4,0
Voltage (V):	49,5
Nbr of parallel cells:	3
Nbr of series cells:	15
Nbr of cells:	45
Capacity (kWh)	2,9
Max Output Power (kW):	53,6
Max Charging Power (kW):	4,3
Charge (Ah):	58,5
Mass (kg):	22,32
Max Current [A]:	585

Table 2.Energy Storage arrangement

7 About the Regenerative Sailplane Performance

As said previously, the final result of the regenerative sailplane feasibility study is the performance data for the regenerative sailplane while flying the same task as the conventional sailplane.

In order to have a qualitative feeling of that, a set of flight energy state plots were built and are shown in Table 3.

The plots show clearly that when cruising at lower speed, the regenerative sailplane is more capable of fulfilling the desired flight task, which is not the case of flying at higher speeds. This occurs because the airframe is not optimized for high speed cruise.

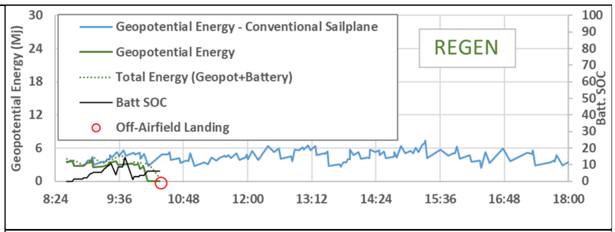
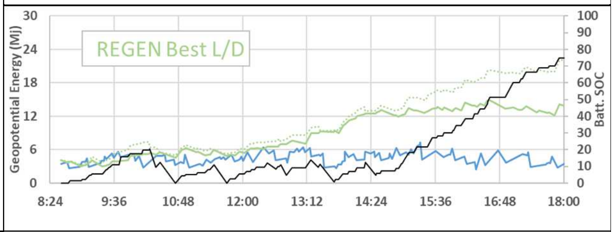
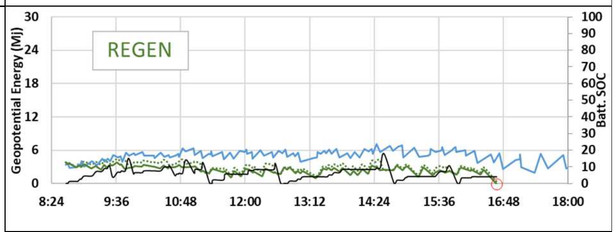
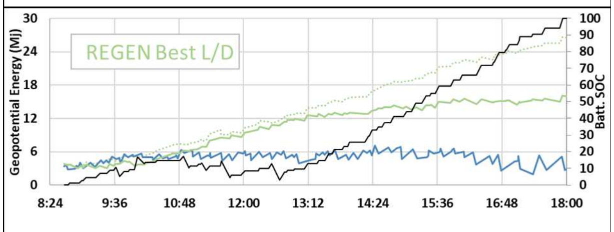
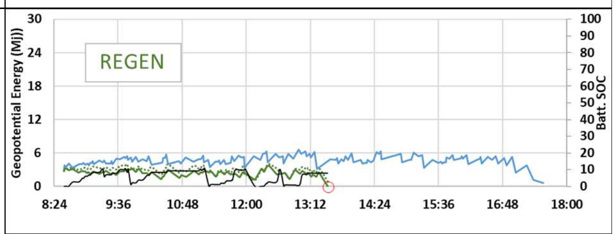
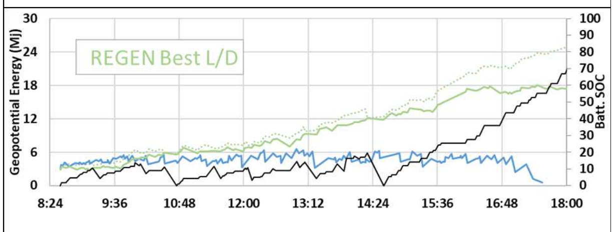
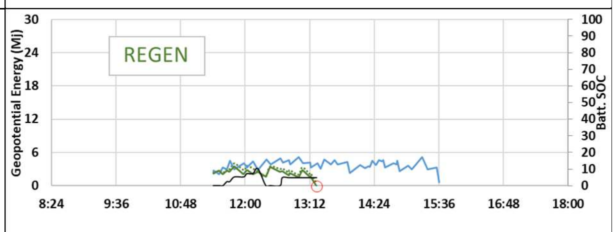
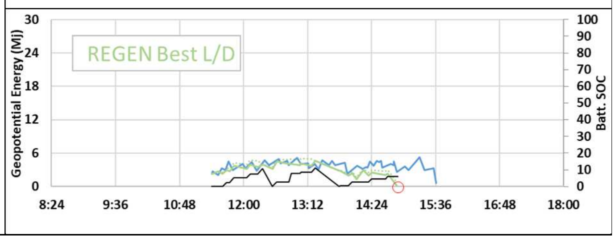
1	
	
3	
	
6	
	
14	
	

Table 3.Examples of Energy History for some flights

8 Conclusions

For the scope for this work, the author considers the following was achieved:

- The problem of regenerative sailplane was formally proposed and some theoretical aspects were discussed, comparing the conventional and the regenerative flight models;
- A comparison of the flight strategies for the conventional and regenerative sailplanes was done and some flight scenarios were discussed;
- A vehicle configuration for fulfilling the regenerative flight task was proposed based on the conversion of a conventional sailplane;
- The actual flight conditions of 36 real-world flights were taken and off-line simulations for the regenerative sailplane were built;
- A discussion on the obtained performance was made after system components sizing was done.

The author hopes that what was shown in this and future works can be used by designers come up with real-life vehicles capable of performing soaring flight with electrical energy regeneration.

9 Topics for Research

The following topics are relevant for subsequent research:

- Implement a Simulink® model of the Propulsive/Regenerative System for on-line simulation integrated into a flight simulator for flight techniques investigation;
- Propose an airframe for the Regenerative Sailplane optimized for the specific task of regenerative flight;
- Investigate the adoption of hybrid batteries/ultra-capacitors energy storage systems for the regenerative sailplane.

10 Nomenclature

V_{avg}	Cross country mean speed	m/s
D	Inter thermal distance	m
t_c	Circling Time	s
H	Height gain in thermal	m
V_c	Acft vertical speed in thermal	m/s
V_s	Acft vertical speed in glide	m/s
t_g	Gliding time	s
t	Total cycle time	s
P_g	Power spent in glide	W
P_c	Power absorbed while circling	W
m	Acft mass	kg
g	Gravity acceleration	m/s^2
C_l	Acft lift coefficient	N/D
C_d	Acft drag coefficient	N/D
C_d	Acft drag coefficient	N/D
V_g	Gliding airspeed	m/s
W	Acft weight	m/s
$\dot{z}$	Acft sink speed	m/s
S	Wing area	m^2
ρ	Air density	kg/m^3
γ	Flight path angle	^{o}
β	Bank angle	^{o}

11 References

[1] F. Hermanspann, “Aerodynamic Efficiency of Gliding Vehicles,” *Technical Soaring,* vol. 18.

[2] F. Thomas, "1OO YEARS OF SAILPLANE DESIGN AND BEYOND," *Technical Soaring,* vol. XXVII, no. July 2003, pp. 61-74, 2003.

[3] Christoph W. Kensche, “THE INFLUENCE OF MATERIALS ON THE DEVELOPMENT OF SAILPLANE DESIGN,” vol. XXVII, nº July 2003.

[4] J. M. Fred Thomas, Fundamentals of Sailplane Design, College Park: College Park Press, 1999.

[5] P. MacCready, “REGENERATIVE BATTERY-AUGMENTED SOARING,” *Technical Soaring,* vol. 23, nº 1, 1999.

[6] J. P. Barnes, “Flight Without Fuel – Regenerative Soaring Feasibility Study,” SAE International., 30 August 2006. [Online]. Available: https://saemobilus.sae.org/content/2006-01-2422.

[8] A. Nishizawa, “FEATHER project in JAXA and toward future electric aircraft,” Arlington, 2016.

[9] R. Niles, “Pipistrel Flies WATTsUP Electric Trainer,” AVweb, 24 August 2014. [Online]. Available: https://www.avweb.com/avwebflash/news/Pipistrel-Flies-WATTsUP-Electric-Trainer-222637-1.html.

[10] J. F. Marchman, Introductory Aircraft Performance, Virginia Tech Aerospace, 1994.

[11] C. D. C. Jr., "The Theory of Soaring in Vortex Shells - Pt 2," *Soaring,* no. May, pp. 8-12, 1961.

[12] W. B. Kagabo and J. R. Kolodziej, "Trajectory determination for energy efficient autonomous soaring," in *Proceedings of the 2011 American Control Conference*, San Francisco, CA, 2011.

[13] Federal Aviation Administration, "Glider Handbook," [Online]. Available: https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/glider_handbook/. [Accessed 2018].

[14] C. D. C. Jr, "THE DESIGN OF SAILPLANES FOR OPTIMUM THERMAL SOARING PERFORMANCE," Langley Research Center, Hampton, 1964.

[15] “OLC Innovations for Soaring,” Segelflugszene gGmbH, [Online]. Available: https://www.onlinecontest.org/olc-3.0/gliding/index.html?c=C0&sc=&st=olc&rt=olc.

[20] Pipistrel, "Pipistrel APIS Self-Launch single seat sailplane Glider from Pipistrel USA," Pipistrel USA, [Online]. Available: https://www.pipistrel-usa.com/apis/. [Accessed 2018].

[21] “StrePla Streckenflugplanung und Auswertung,” [Online]. Available: http://www.strepla.de/StrePla4/english/indexEnglish.html. [Acesso em 2018].

[22] D. Ansean, V. García, M. González, J. Viera, C. Blanco and J. Antuna, "DC internal resistance during charge: analysis and study," in *EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, Barcelona, Spain, 2013.

[23] D. Kim, K. Koo, J. J. Jeong, T. Goh and S. W. Kim, "Second-Order Discrete-Time Sliding Mode Observer for State of Charge Determination Based on a Dynamic Resistance Li-Ion Battery Model," *www.mdpi.com/journal/energies,* 2013.

[24] L. Lu, "Battery performances testing and analyzing for BMS," Tsinghua University, 2011.

[25] Richtek Technology Corporation, "Li-ion Battery and Gauge Introduction," Hsinchu, Taiwan, R.O.C., 2014.

[26] N. Somakettarin and T. Funaki, "Study on Factors for Accurate Open Circuit Voltage Characterizations in Mn-Type Li-Ion Batteries," MDPI, Basel, Switzerland, 2017.

[27] M. Hepperle, "JavaProp - Design and Analysis of Propellers," [Online]. Available: https://www.mh-aerotools.de/airfoils/javaprop.htm. [Accessed 2018].

[28] C. Fries, "Obba: A Java Object Handler for Excel, LibreOffice and OpenOffice. - Access Java objects and methods via user defined functions.," [Online]. Available: http://obba.info/. [Accessed 2018].

[29] RTCA, Incorporated, "Software Considerations in Airborne Systems and Equipment Certification," 2012.

[30] SAE International, "Guidelines For Development Of Civil Aircraft and Systems," 2010.

[33] M. Agostini, S. Brutti, M. A. Navarra, S. Panero, P. Reale, A. Matic e B. Scrosati, “A high-power and fast charging Li-Ion battery with outstanding cycle life,” *Scientific Reports. DOI:10.1038/s41598-017-01236-y,* 2017.

[34] P. Morelli, “Development of the Microlift Glider,” *Technical Soaring,* vol. 30, nº 1/2, 2006.

[36] P. Morelli, “ELECTRICAL. AND SUN POWERED GLIDERS: DO THEY REQUIRE A DEFINITION OF NEW F.A.I. CLASSES?,” *Technical Soaring,* vol. XXII.

[38] C. D. C. Jr., "The Theory of Soaring in Vortex Shells - Pt 1," *Soaring,* no. April, pp. 8-13, 1961.

[35] P. Morelli, “Cruising Flight of Light Aircraft and Motorgliders,” *Technical Soaring,* vol. XVII, 1999.

[37] C. D. C. Jr., “The Theory of Soaring in Vortex Shells - Pt 3,” nº June, pp. 6-8, 1961.

[40] B. H. Carmichael, “DESIGNING TOWARD A ONE FOOT PER SECOND SINKING SPEED,” *Technical Soaring,* vol. XX, pp. 118-121.

[42] E. Schöberl, "SOLAR POWERED ARCRAFT DESIGN," *Technical Soaring,* vol. XV No 2, pp. 38-47, 1989.

[60] Texas Instruments, “Battery Monitoring Basics,” Dallas, Texas, 2012.

[62] A. RAHMOUN e H. BIECHL, “Modelling of Li-ion batteries using equivalent circuit diagrams,” *PRZEGLĄD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097,* p. R. 88 NR 7b/2012, 2012.

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