Advances in Aircraft and Spacecraft Science, *Vol. 9, No. 1 (2022) 17-37*
https://doi.org/10.12989/aas.2022.9.1.017

Full composites hydrogen fuel cells unmanned aerial vehicle with telescopic boom

E. Carrera[1,2], M. Verrastro[3] and Alberto Boretti*[4]

[1]Department of Mechanical and AeroSpace Engineering, Politecnico di Torino, c.so Duca degli Abruzzi, Torino, 10129, Italy.
[2]Deanship of Research, Prince Mohammad Bin Fahd University, P.O. Box 1664, Al Khobar 31952, Kingdom of Saudi Arabia
[3]Leonardo Company, Piazza Monte Grappa n. 4, 00195 Rome, Italy
[4]Independent Scientist, Chancellor Avenue, 3083 Bundoora, Australia

(Received December 1, 2021, Revised December 9, 2021, Accepted December 10, 2021)

Abstract. This paper discusses an improved unmanned aerial vehicle, UAV, configuration characterized by telescopic booms to optimize the flight mechanics and fuel consumption of the aircraft at various loading/flight conditions. The starting point consists of a full-composite smaller UAV which was derived by a general aviation ultra-light motorized aircraft ULM. The present design, named ToBoFlex, extends the two-booms configuration to a three tons aircraft. To adapt the design to needs relevant to different applications, new solutions were proposed in aerodynamic fields and materials and structural areas. Different structural solutions were reported. To optimize aircraft endurance, the innovative concept of Telescopic Tail Boom was considered along with two different tails architecture. A new structural configuration of the fuselage was proposed. Further consideration of hydrogen fuel cell electric propulsion is now being studied in collaboration between the Polytechnic of Turin and Prince Mohammad Bin Fahd University which could be the starting point of future investigations.

Keywords: electric propulsion; full composite aircraft; hydrogen fuel cell; structural design; UAV

1. Introduction

UAVs (Unmanned Aerial Vehicles) represent the major novelty in the aircraft world of the last three decades. The proliferation of UAVs continues to accelerate, with a growing number of companies, countries, and innovative designs entering the market. Before the 1990s, Israel alone truly committed to the development of unmanned military aircraft to reduce the loss of pilots and aircraft on dangerous reconnaissance and surveillance missions. Afterward, in consequence of the Pioneer success in Operation Desert Storm, aerospace firms in the U.S, Europe, and Asia updated the UAV concepts with new technologies and materials. A few years later newer UAVs were sent into service in the Balkans helping to enforce no-fly zones and preventing Iraq’s military from conducting surprise attacks on its people. By the time of Operation Iraqi Freedom following the September 11, 2001, terrorist attacks, South-west Asia became a proving ground for a wide array of

*Corresponding author, Professor, E-mail: a.a.boretti@gmail.com

http://www.techno-press.org/?journal=aas&subpage=7 ISSN: 2287-528X (Print), 2287-5271 (Online)

UAVs, led by the Predator. The jet-fighter-sized Global Hawk was sent into service while still a prototype. The AAI-built Shadow had used by the Army and Marine Corps, primarily for reconnaissance, target acquisition, and battle-field. One of the most popular UAVs in Southwest Asia is the 4-lb Raven, which warfighters hurl into the air like javelins.

UAVs also have seen increasing use in other parts of the world from Eastern Europe to the Horn of Africa, from antipiracy patrols over the Straits of Malacca to drug and illegal alien interdiction along national borders, to agricultural, fire detection, wildlife tracking, and weather observation missions worldwide.

Today less expansive computer technology has enabled more and better sensors; more durable composite materials for skin and structure, combined with more powerful lightweight powerplant and good structural and aerodynamic solutions, increased both payload and range. The development of GPS navigation and location gave UAVs precision in reaching designated targets. In this manner, it is possible to achieve performance relevant to many various mission profiles.

Many contractors, from different private and governmental areas, are approaching this world. As unmanned aircraft could serve many different applications, they were generally classified as:

- Micro UAV (better MAV): reduced dimensions and weights. Short endurance (30-60 min) and range (3-10 km).
- Tactical UAV (TUAV): Range of about 100-500 km and endurance 2-7 h. Tactical purposes.
- Endurance UAV: endurance more than 24 h, medium-high altitude. Also divided in:
  - Medium Altitude Endurance UAV (MAE)
  - High Altitude Endurance UAV (HAE or HALE)
  - Low Observable-High Altitude UAV (LO-HAE)

This work describes an innovative design of a UAV named ToBoFlex (Two Boom Flexible) (Carrera and Triffiletti 2009). It is derived by an ultralight full ULM composite aircraft named Millenium, which originated the Sky-Y UAV (Carrera and Triffiletti 2009). A unique prototype of Sky-Y aircraft was derived by the ULM. Such a prototype has successfully flight for about then years by establishing endurance European record in the related 1ton category of aircraft. Sky-Y, due to project constraints was not fully optimized due to the need of using wings, and tails (and related to the use of available molds) of Millennium.

Millennium ULM used composite materials enabling high performances (Maximum weight: 450 kg; Wing surface S=9.96 m^2; Load factors n: +9/-6 g; Endurance: 6 h; Cruising speed 260-306 km/h). CAD (Computer-Aided Design) systems were used to design it; FEM (Finite Element Model) methodology has been used to carry on structural analyses. Static, modal, and buckling analyses have been accomplished. Production Process consists of three phases: mold construction, structure production process, and structural item assemblage.

Sky-Y UAV uses some parts of the ultralight aircraft Millennium; for example, the wing and the horizontal tail surface. The fuselage is composed of external skin and an internal primary structure. The lower part of the skin has structural functions. The upper part has only shape functions. The internal structure is composed of bulkheads, two panels, a spar under the lower plane, and a spar between the planes.

The details of the Millennium Sky-y project are presented by Mul2 Research Group (2021) and the interested reader can find them in the publications listed there.

The present paper is drawn up by starting from these previous experiences. It aims to propose a flexible 3 tons UAV that could play a significant role in the UAV market. The two booms are expandable to better accommodate optimized flight mechanics conditions, due to various velocities, altitude, and weight distribution. An MDO analysis has been made by accounting for various flight conditions and payload configurations. Simplified aerodynamic analyses have been used to compute lift and drag at the various flight conditions and to optime wing profiles. A classical carbon-fuel motorized version is analyzed along with detailed structural Finite Element analysis. The flexibility of ToBoFlex has been finally used to propose a hydrogen propelled zero-emission version which could be investigated further in future projects.

In the quest for CO_2 emission-free aviation, electric propulsion, or the use of hydrogen as a fuel (hydrogen council 2021) has been proposed. In addition to the opportunity of being used as combustion fuel in an otherwise conventional aircraft propulsion system (Boretti 2021), electric propulsion can be made better with hydrogen fuel cells than batteries, thanks to the much better specific weight. Electric propulsion in aircraft is still in the early stages. The opportunity of using hydrogen fuel cells rather than lithium-ion batteries is however receiving attention, with demonstration aircrafts such as the HY4 already successfully tested (Cummins 2021).

The design of hydrogen fuel cells aircraft is covered in many works in the scientific literature such as (Bradley *et al.* 2007, Guynn *et al.* 2004, Kim and Kwon 2012, Bradley *et al.* 2008, Ng and Datta 2019, Lapeña-Rey *et al.* 2010, Bradley *et al.* 2006, Friedrich *et al.* 2009, Kallo 2015, Arat *et al.* 2020, Baroutaji *et al.* 2019, Özbek *et al.* 2020, Brelje and Martins 2021, Oh 2018) just to name a few. Even wider coverage is provided for hydrogen fuel cells cars, that are close to mass production commercial products.

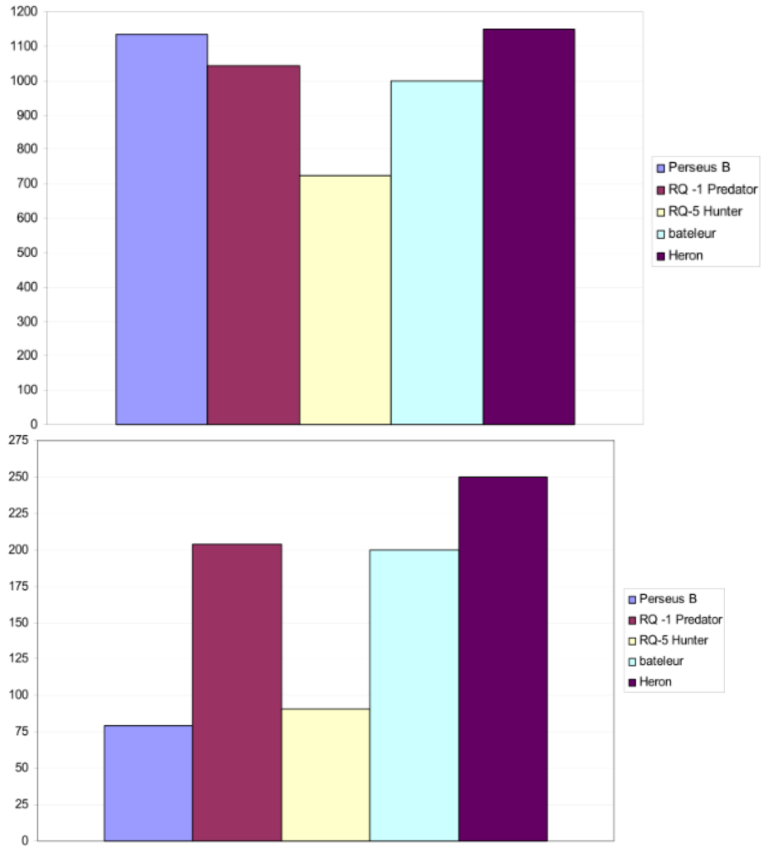

Fig. 1 Comparison of empty weight (top) and payload capability (bottom)

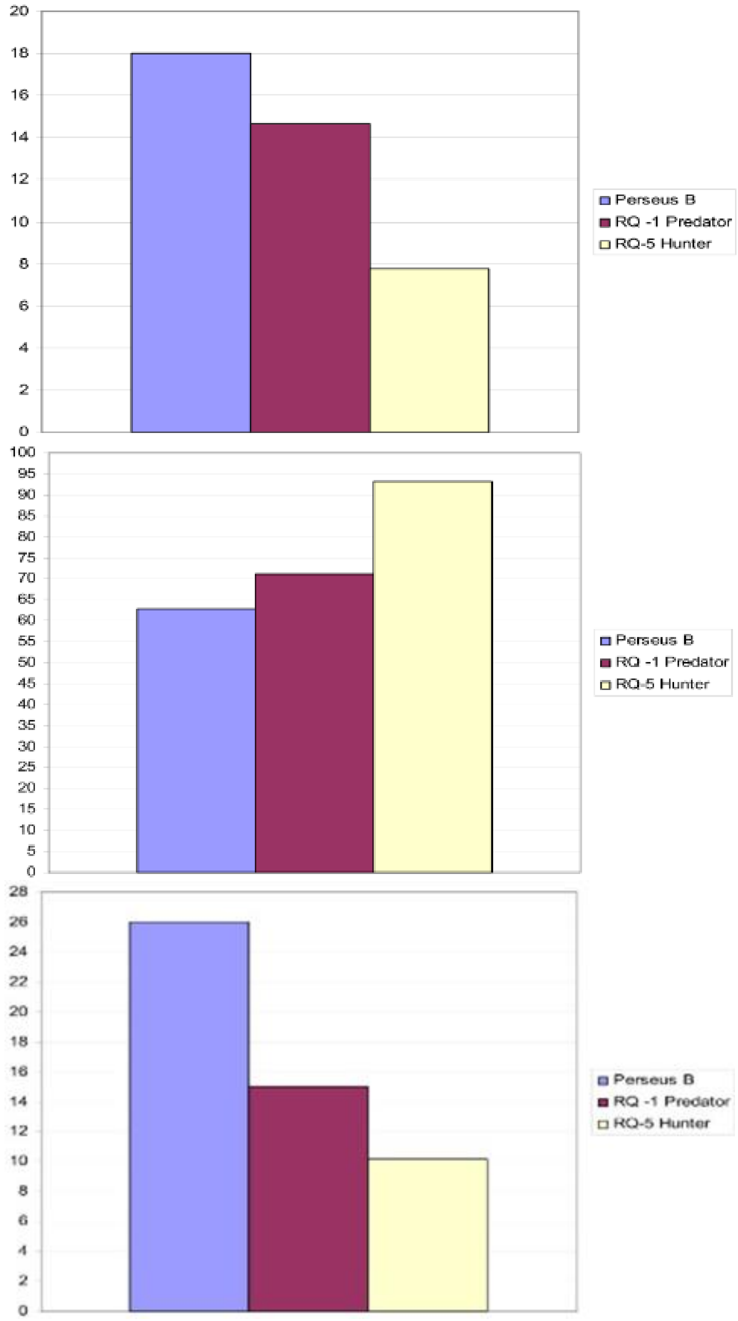

Fig. 2 Comparison of wing surface (top), wing load (middle), and aspect ratio (bottom)

The paper has been organized as follows:
Sec. 2 and 3 encompass the various steps of the conceptual design of ToBoFlex.
The main characteristics are drawn in Sec. 4.
Sec. 5 is devoted to the hydrogen fuel cell electric propulsion concept.

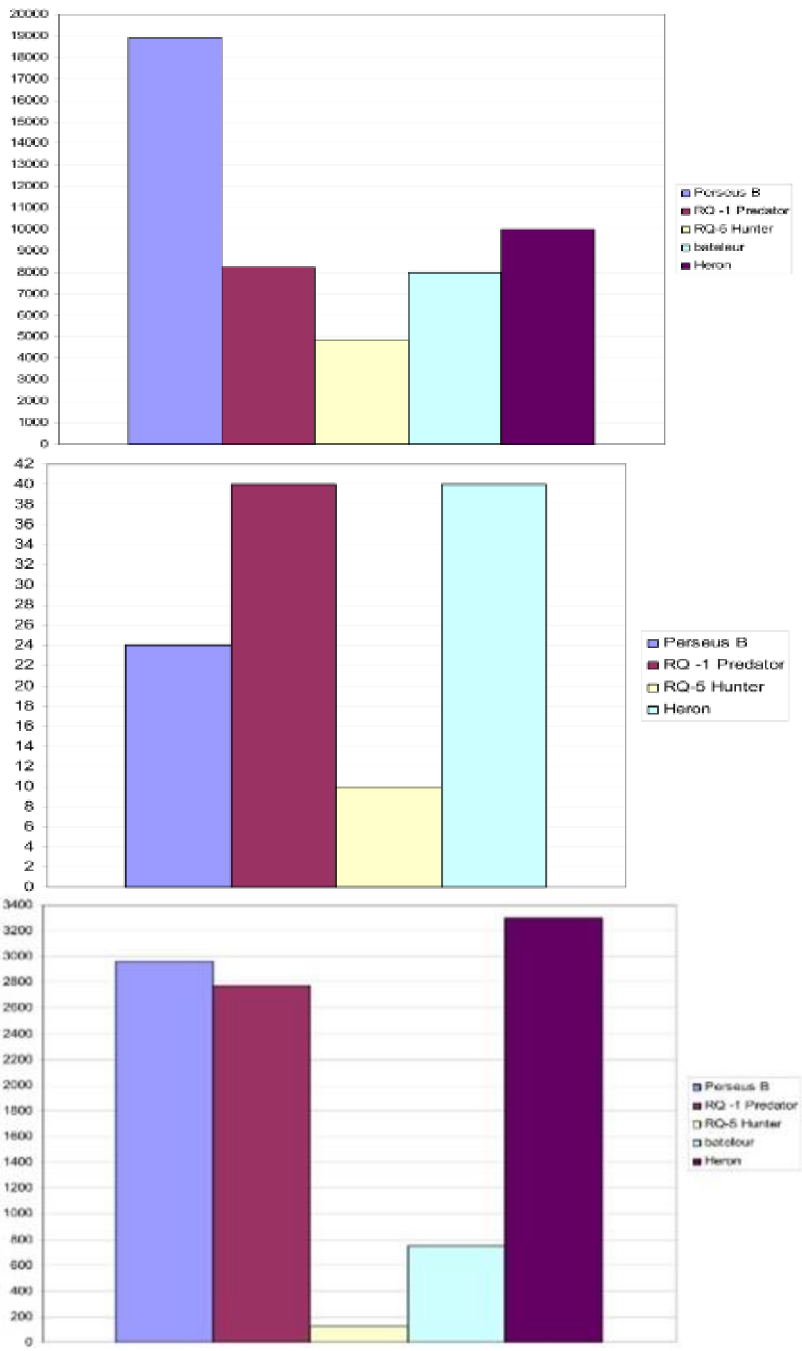

Fig. 3 Comparison of flight altitude (top), endurance (middle), and maximum range (bottom)

The basic design will have to be revised to include the specific fuel cell electric propulsion system adopted.

In Sect. 6 conclusions and perspectives are then reported.

2. The ToBoFlex aircraft

A comparative analysis of significant properties of the UAV-related aircraft is made in Figs. 1-3. Empty weight and payloads capability are given in Fig. 1. Wing surfaces, loadings, and aspect ratio are instead compared in Fig. 2. Flight performance (altitude, endurance, and maximum range) are finally drawn in Fig. 3.

Numbers related to UAVs of the same category are given to clearly state the possibility of making

Table 1 main data of ToBeFlex

geometry			
wing			
wing span	b	18	m
wing surface	S	22.5	m^2
elongation	AR	14.4	
taper	λ	1.5	
chord root	c_{root}	1.35	m
chord tip	c_{tip}	0.9	m
M.A.C.	c	1.25	m
horizontal tail plane			
span tail	b_t	6	m
surface tail	S_t	5.1	m^2
elongation	AR_t	7.06	
taper	λ_t	1	
chord root	$c_{r\,t}$	0.85	m
chord tip	$c_{t\,t}$	0.85	m
M.A.C.	c_t	0.85	m
vertical tail plane			
n° of drift	$n°_{vt}$	2	
chord root	$c_{r\,vt}$	1.8	m
chord tip	$c_{t\,vt}$	0.85	m
height of drift	h_{vt}	1.3	m
surface of drift	S_{vt}	1.72	m^2
fuselage			
length	l_{fus}	7	m
principal diameter	d_{fus}	1	m
other dimensions			
height of tail plane vs. wing plane	z_t	1.3	m
distance between wind and tail plane foci	l_{ff}	5	m
weights			
max. weight	$TOGW$	1500	kg
comb./pay weight	$W_{f\,max}$	700	kg
wing load	W/S	66.67	kg/m^2
performances			
operating altitude	z_{op}	10000	m
cruise speed	v_{cr}	180	km/h
cruise efficiency	e_{cr}	21.04	
endurance (hours)	d_h	144.1	h
range (km)	r_{km}	11292	km

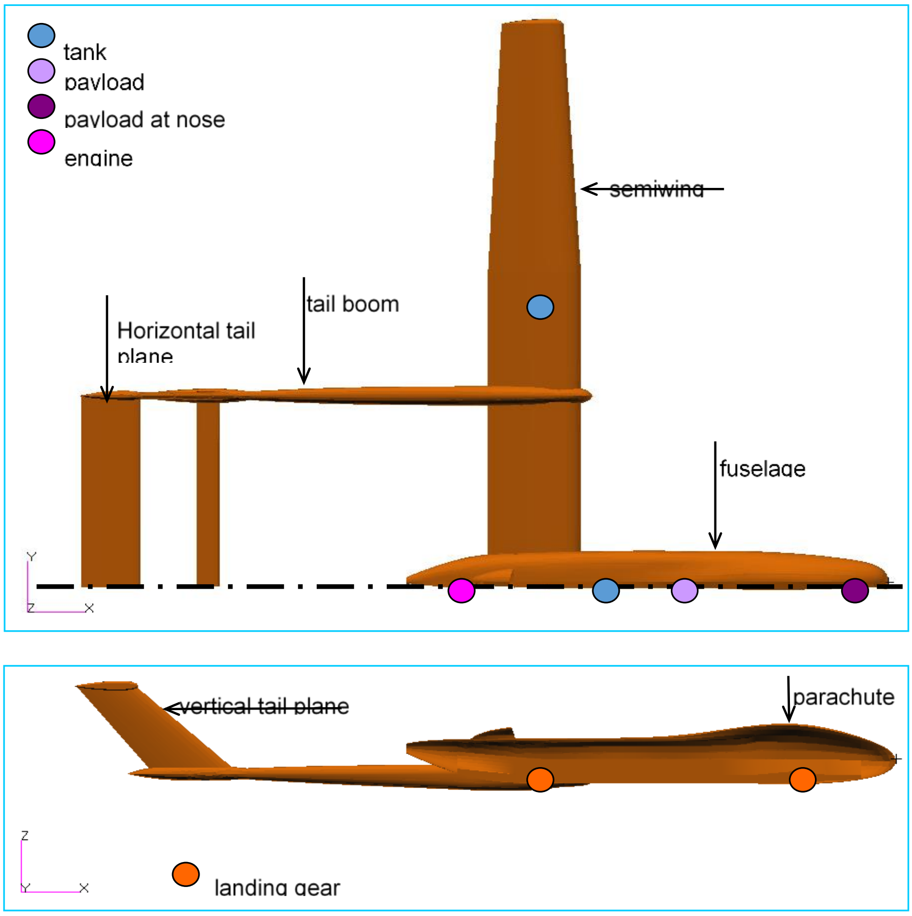

Fig. 4 Geometry of ToBeFlex

a new one. From this analysis as well as others not detailed herein, the configuration depicted in Table 1 and Fig. 4 has been proposed to build the ToBoFlex configuration to be analyzed further.

3. Results of MDO analysis

3.1 Aerodynamics

ToBoFlex would be a UAV with higher performances, higher endurance (major fuel capability), higher payload, higher volume, higher weight than its ancestor Sky-Y. So it is necessary to modify the original wing by researching a more carrying wing profile and, the fuselage, to obtain greater dimensions fitting new fuel and payload requests.

Three possibilities have been studied:

- The model with the low tail plane
- The model with a high tail plane
- The model with a double tail plane

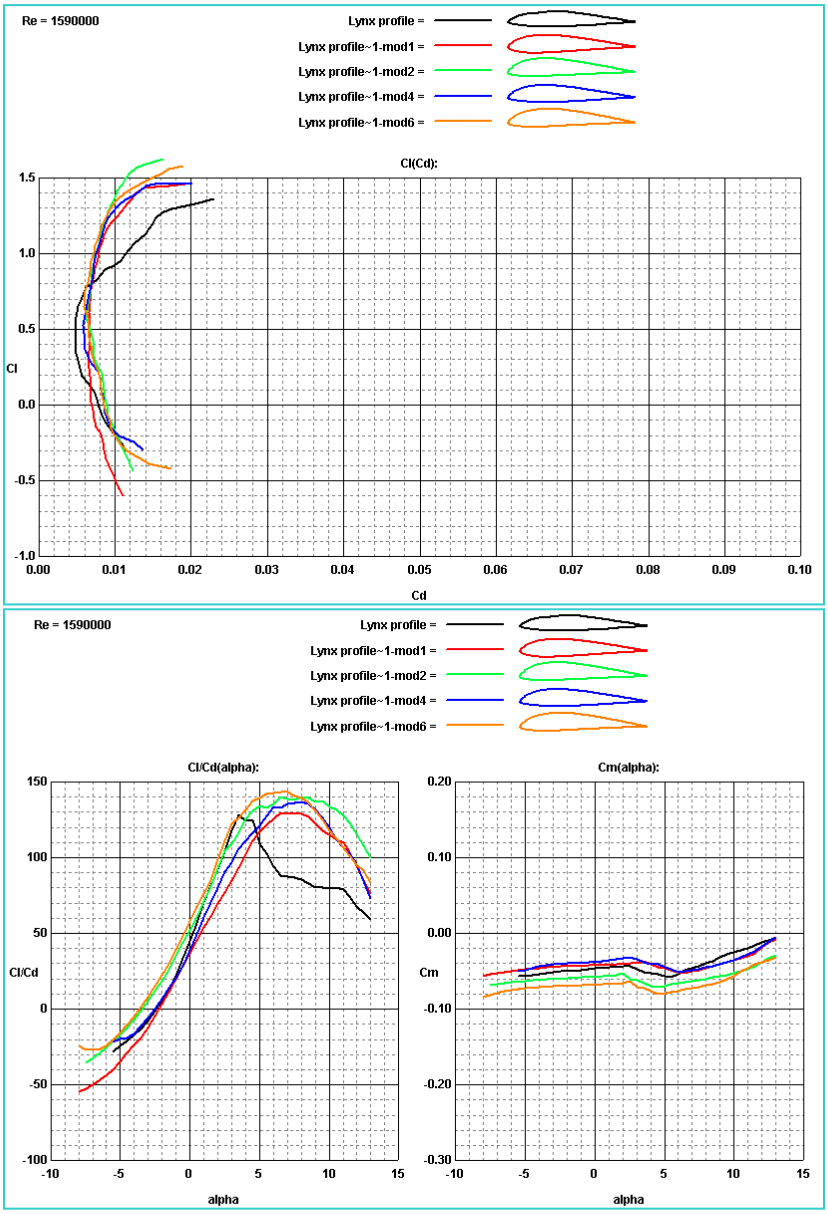

Fig. 5 Example of the made wing profile analysis

From the aerodynamic point of view, the second solution can reduce turbulences due to the pusher propeller; on the other hand, this solution can cause structural problems, especially in terms of dynamic results. These problems can be solved by putting a bar among the tail boom and by connecting it to the fairing (third solution).

The new wing profile has been obtained from a study and a comparative evaluation of existent profiles, by suggesting possible modifications. High incidence capability is essential to increase endurance. To prevent flux detachment, the leading-edge was made rounder by changing its radius from 1.43 mm to 1.6 mm. Related solutions are worked out through XFoil aerodynamic software. By using XFoil the Tail Plane profile was studied starting from the existent profile NA012-63. For the Elevator profile, the mobile surface is extended at 35% of the total profile. The 'Lifting line theory' was used to pass from two-dimensional to three-dimensional profiles.

Various wing profiles have been analysed. Fig. 5 shows some x-foils type analysis performed to select the profile with optimized aerodynamic efficiency. Selected profile analysis has been made, e.g., Maximum lifting coefficient CL, Low drag coefficient CD at the various angle of attack vs Maximum efficiency. The wing profiles with the following data were chosen: 14% of maximum thick at 25% of wing chord; 4% of maximum curving at 35% of the wing chord.

The wing aerodynamic was built by using available free-to-use software such as Tornado. A typical analysis is the one in Fig. 6, where vortex lines are traced.

Results in terms of lifting coefficients and polar of the wing are those in Fig. 7.

3.2 Flight mechanics

Flight mechanics charts were calculated by using common regulations. Suitable adjustments have been brought. For example, cruising and diving velocity are lower w.r.t. regulations similarly to Tornado, the same for $n+$ and $n-$.

By starting from a hypothetical masses distribution, different ToBoFLex configurations were studied by using ad hoc developed software.

Significant changes, relevant to different configurations, were registered in terms of the attitude of flight and tail incidence. C_{m0} remains the same because no change in terms of geometry has been brought. Fluctuation of C_m is greater for the configuration with a higher payload in the front portion of the fuselage when compared with a similar aircraft configuration with a more distributed payload along the fuselage.

The flight envelope was obtained by available regulations like the one in Fig. 8. This has been the basis to define the loading configuration to be considered in the structural analysis.

Related data of loading factors vs relevant speeds have been put in Table 2.

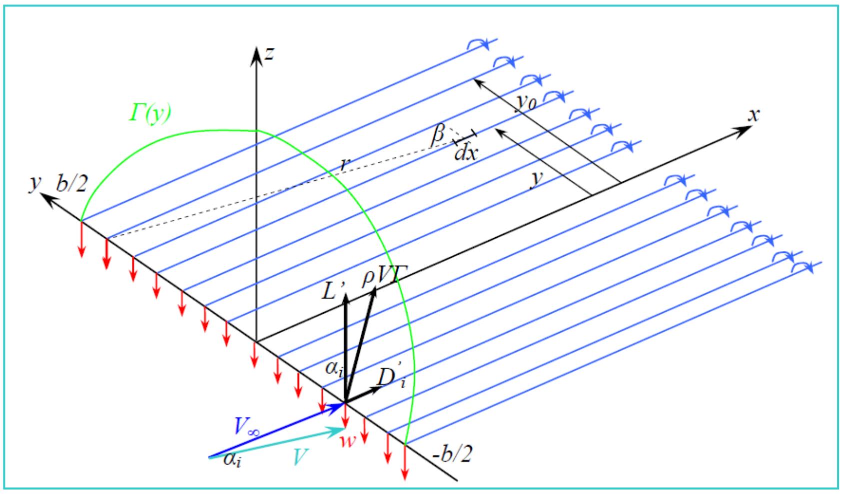

Fig. 6 Sketch of the aerodynamic model of the wing

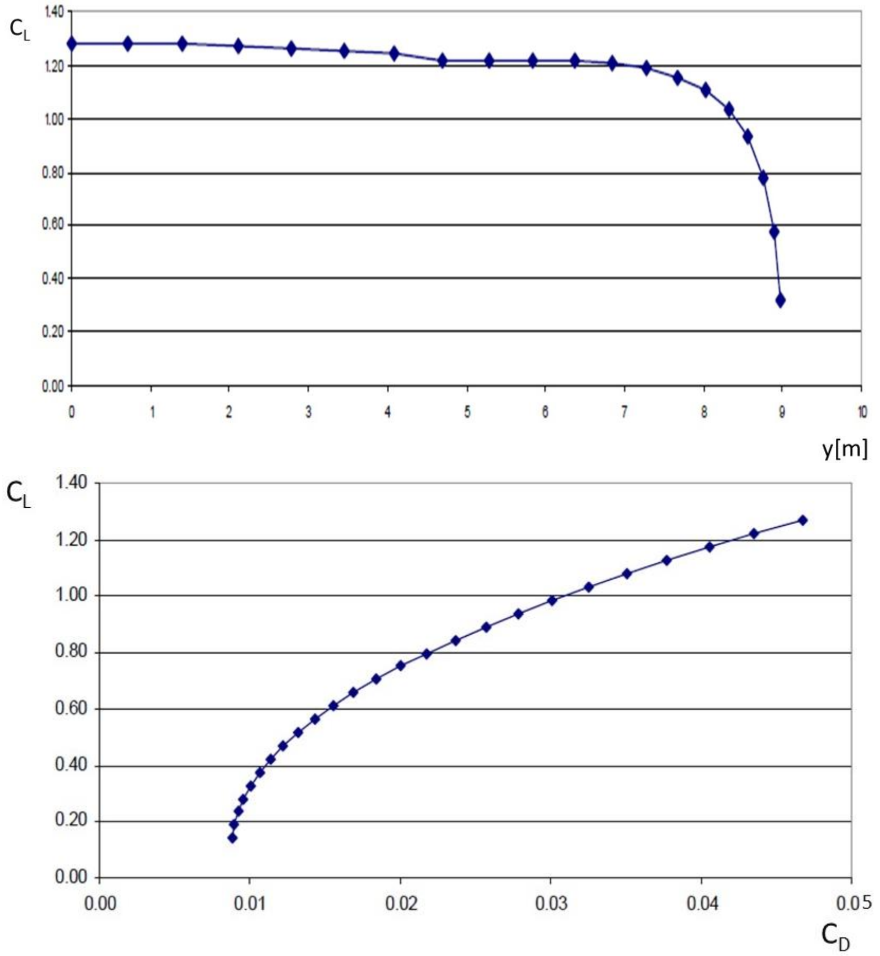

Fig. 7 Main results for the aerodynamic of the wing. C_L vs. y (in m) and C_L vs. C_D

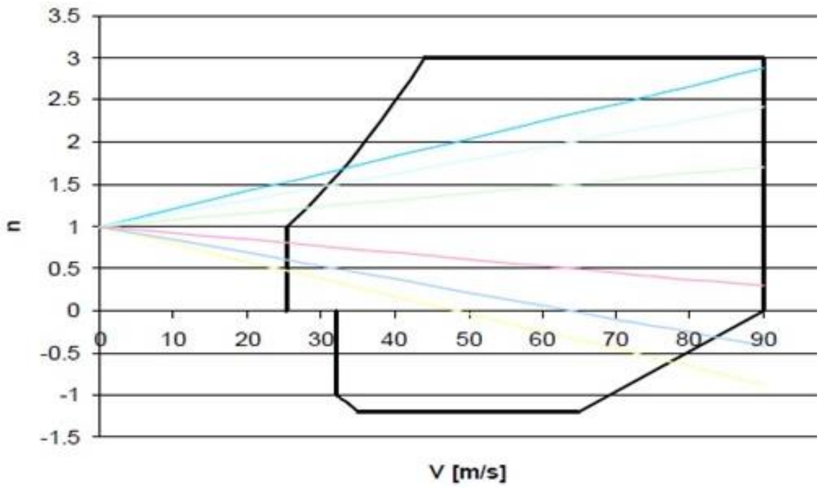

Fig. 8 *n*-*v* diagram of ToBoFlex with envelope diagram *z*=0

Table 2 Value of significant loading factors and aircraft speeds

n	$V\,(Cl_{max})$	$V\,(Cl_{min})$	n	$V\,(Cl_{max})$	$V\,(Cl_{min})$
1	25.39	32.06	-1.00	43.75	55.23
1.25	28.39	32.46	-1.03	48.91	55.92
1.5	31.10	32.85	-1.05	53.58	56.59
1.75	33.59	33.24	-1.08	57.87	57.26
2	35.91	33.62	-1.10	61.87	57.93
2.25	38.09	34.00	-1.13	65.62	58.58
2.5	40.15	34.38	-1.15	69.17	59.23
2.75	42.11	34.75	-1.18	72.55	59.87
3	43.98	35.12	-1.20	75.77	60.50

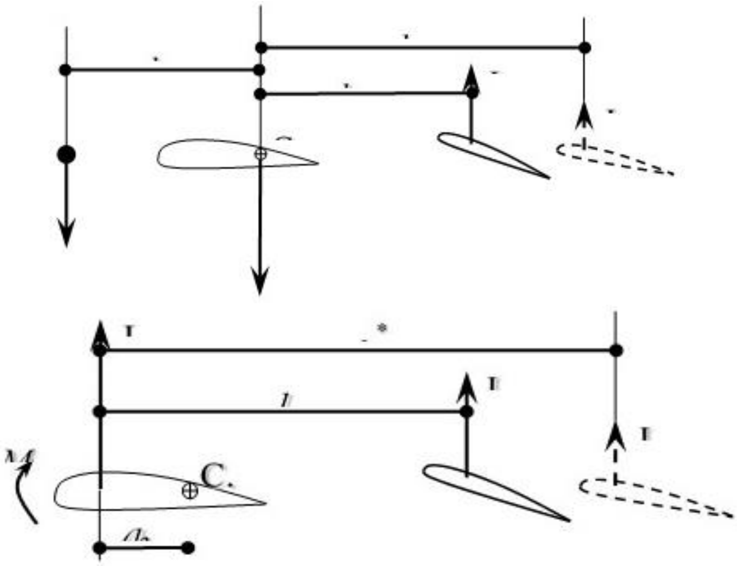

Fig. 9 Sketch of the telescopic boom geometry

3.3 Telescopic booms effects

Telescopic tail booms were studied to optimize aircraft endurance. Through it is possible to obtain a variable inter-focal length to manipulate aircraft efficiency.

Telescopic tail boom peculiar aspects are the reduction of the tail lift and therefore of the drag and the trimming of loads placed on fuselage prow.

An example of the movable tail plane effect is reported below. In this case, a low load on the prow (3°conf.) gives a low difference if the inter-focal distance changes.

In terms of efficiency, by considering the fixed tail plane, only for a small timeframe the aircraft can be in the optimal attitude in a flight. With the movable tail plane, the aircraft can fly for more time in maximum efficiency conditions during a single flight.

The significant effects of the two telescopic booms are shown in Fig. 9. Telescopic tail booms were mainly introduced to optimize aircraft endurance. Through it is possible to obtain a variable inter-focal length to manipulate aircraft efficiency. Telescopic tail boom peculiar aspects:

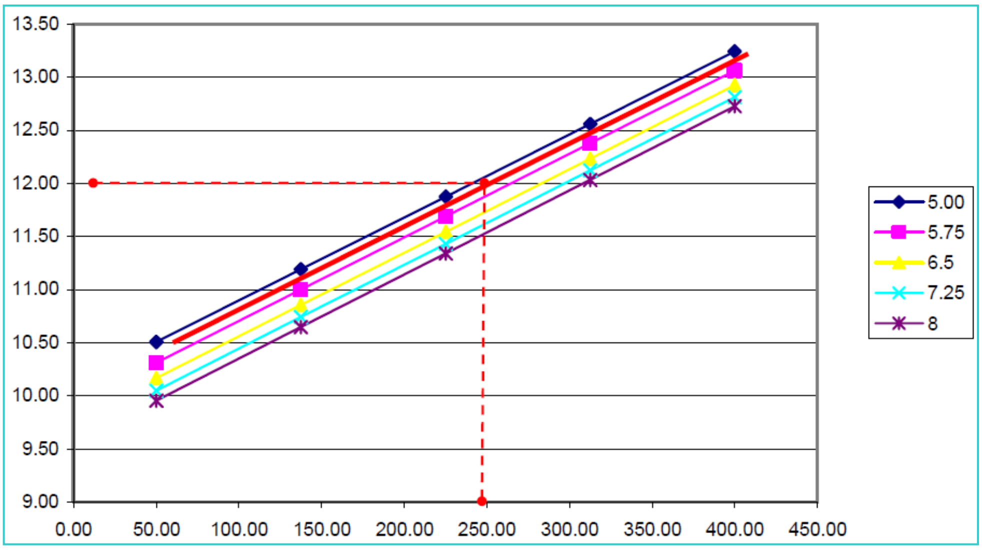

Fig. 10 attitude vs Wfuel. The different curves represent the length of the different boom

- Reduction of the tail lift and therefore of the drag
- Trimming of loads placed on fuselage prow

By varying the distance between wings and tails, by acting on the telescopic booms, significant changes are obtained in the whole aircraft performance. The endurance is shown in Fig. 10.

Concerning Fig. 10, in the case of the fixed tailplane, hypothetical maximum efficiency at 12° (red curve). Only for a moment, the aircraft will be in this optimal attitude of flight due to fuel consumption. By changing the length of the booms it is possible to obtain the best efficiency attitude (12°) also with different fuel weight, and so for a longer flight time.

As far as the tails, the two cases should be outlined. Fig. 11 presents the model with the low tail plane and the model with the high tail plane.

From the aerodynamic point of view, the second solution can reduce turbulences due to the pusher propeller; on the other hand, this solution can cause structural problems especially in terms of dynamic results. These problems can be resolved by putting a bar among the tail boom and by connecting it to the fairing.

3.4 Structural design

The fuselage is composed of external skin and an internal primary structure. The lower part of the skin has structural functions. The upper part has only shape functions. The internal structure is composed of bulkheads, two panels, a spar under the lower plane, and a spar between the planes. The wing is composed of the main spar, a secondary spar, twenty ribs, and the external skin. Materials used for sandwich panels and laminates of the structure are:

- PVC: isotropic material used for sandwich panels core;
- Fabric lamina: composite material, 2-D orthotropic, fibers direction ±45 degrees and a warp-yarn ratio of 1:1. It is used for sandwiches skins and spar webs. Each lamina is 0.2 mm thick;
- unidirectional HS lamina: composite material, 2-D orthotropic. Used to realize the spar heads laminates, each lamina is 0.3 mm thick.

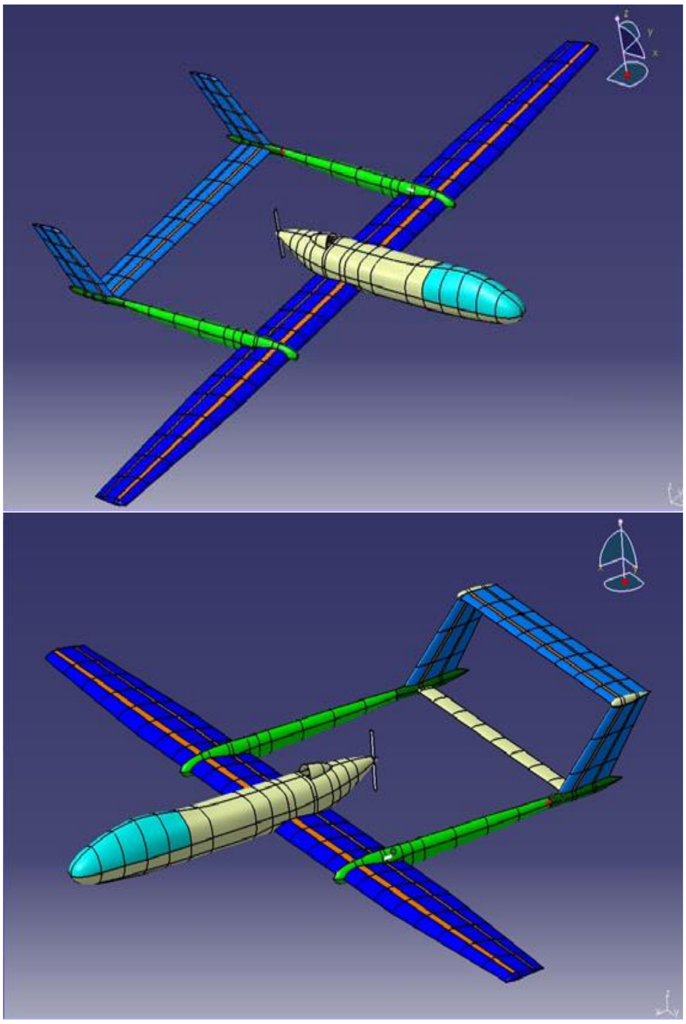

Fig. 11 The model with the low tail plane (left) and the model with the high tail plane (right)

For every component of the aircraft symmetric lamination lay-up is used. The laminate is composed of one skin of fabric oriented at +45 degrees (0.2 mm thick), a PVC core (0.3 mm), and another skin of fabric oriented a +45 degrees (0.2 mm).

Aircraft structure was tested for various loading conditions reported in terms of linear and angular accelerations. These conditions contemplate both symmetric and non-symmetric manoeuvres. Various weight conditions were taken into account to consider different phases of the flight.

Aerodynamic loads, related to linear or angular acceleration, were applied to the wing and tail structures.

Failure Indices results show that values greater than one are located in small and concentrated zones of the structure and are caused by the size of the mesh grid.

For different locations in the structure, the tensile state was analyzed. For each monitoring station, diagrams were obtained. These are used to evaluate if the tensile state in a location is acceptable or not.

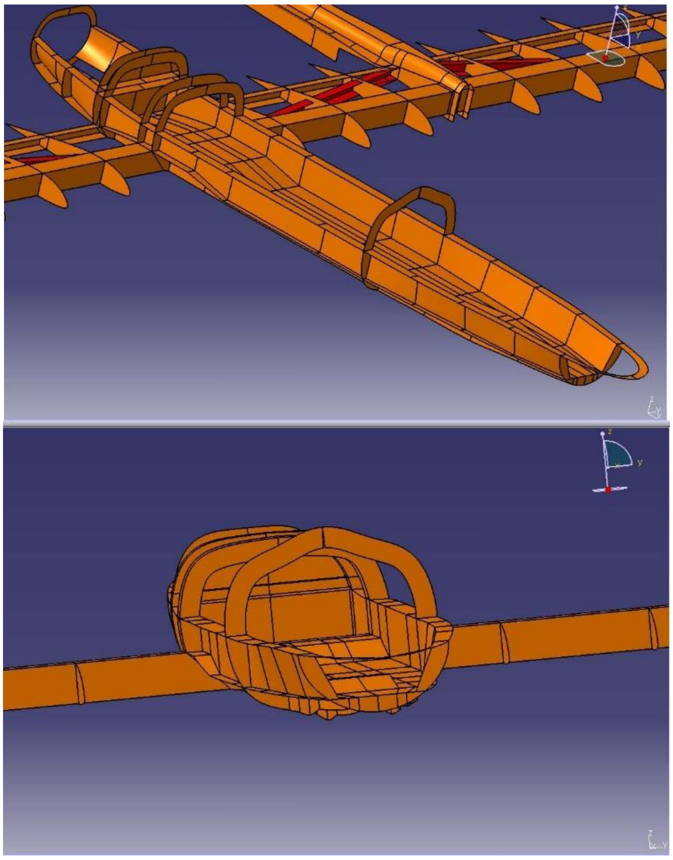

Fig. 12 fuselage structure

A Dynamic Free Vibration Analysis is made for the whole aircraft in free-flight conditions.

The first modes of vibration are related to the tail. A lot of coupled wing-tail-fuselage modes also appear. This coupling effect is caused since the first mode of vibration of the wing is anti-symmetric. This does not agree with results for conventional aircraft, but in this UAV the tail is directly attached to the wing. Anyway, the first symmetric mode shows more or less the same frequency.

The fuselage structure (Fig. 12) is not classical. This structure is resistant and stiff. It is characterized by two longerons jointed with a plane ('omega' structure) and two lateral lengthening that together with the skin make a lateral body. This type of fuselage architecture can save instrumentations and avionics in case of ground impact.

The wings have a typical classical structure with two longerons (C-section) and a central body. It passes through the fuselage and thanks to composite materials properties, makes a single rigid body together with the fuselage. This structure will bring all wing loads and will be a support for tail boom and landing gear.

The tail is connected to longerons using strengthening slanting longeron.

From static analyses, it is demonstrable that if strengthening oblique longeron is eliminated from the structure, numerical results didn't change.

The Front Landing Gear is seated and leaned on a frame that is a strong area.

The same idea was applied for Main Landing Gear that is seated in the boom connection area.

The difference in Fuel Mass provides a mitigating effect in terms of structural solicitations. By considering both these cases is possible to study the structural effect on the aircraft in different flight phases.

For the structural analysis, MSC Nastran and MSC Patran were used. Some results are presented in Fig. 13.

In this analysis propulsive forces were not considered; stresses in the rear fuselage area are due to inertial forces only, caused by the engine mass. For cases, 1&2 and the single-high tail plane configuration, greater stresses concentration (836MPa) are present on engine conjunctions and the wing-fuselage connection. Failure indexes, major than one, are due to computational error. Displacement results show a structural warping opening out the tail boom.

Same to a single tail plane, stresses relevant to the configuration with the double tail plane are lower than the critical level but now the tail plane twist doesn't take place.

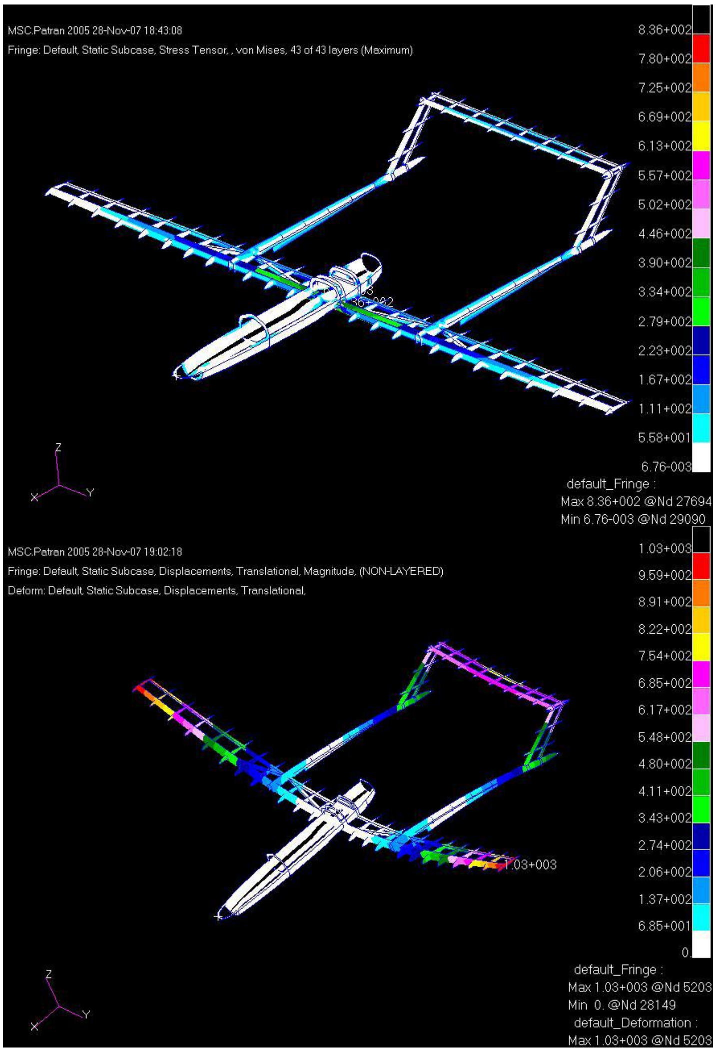

Fig. 13 Structural analysis

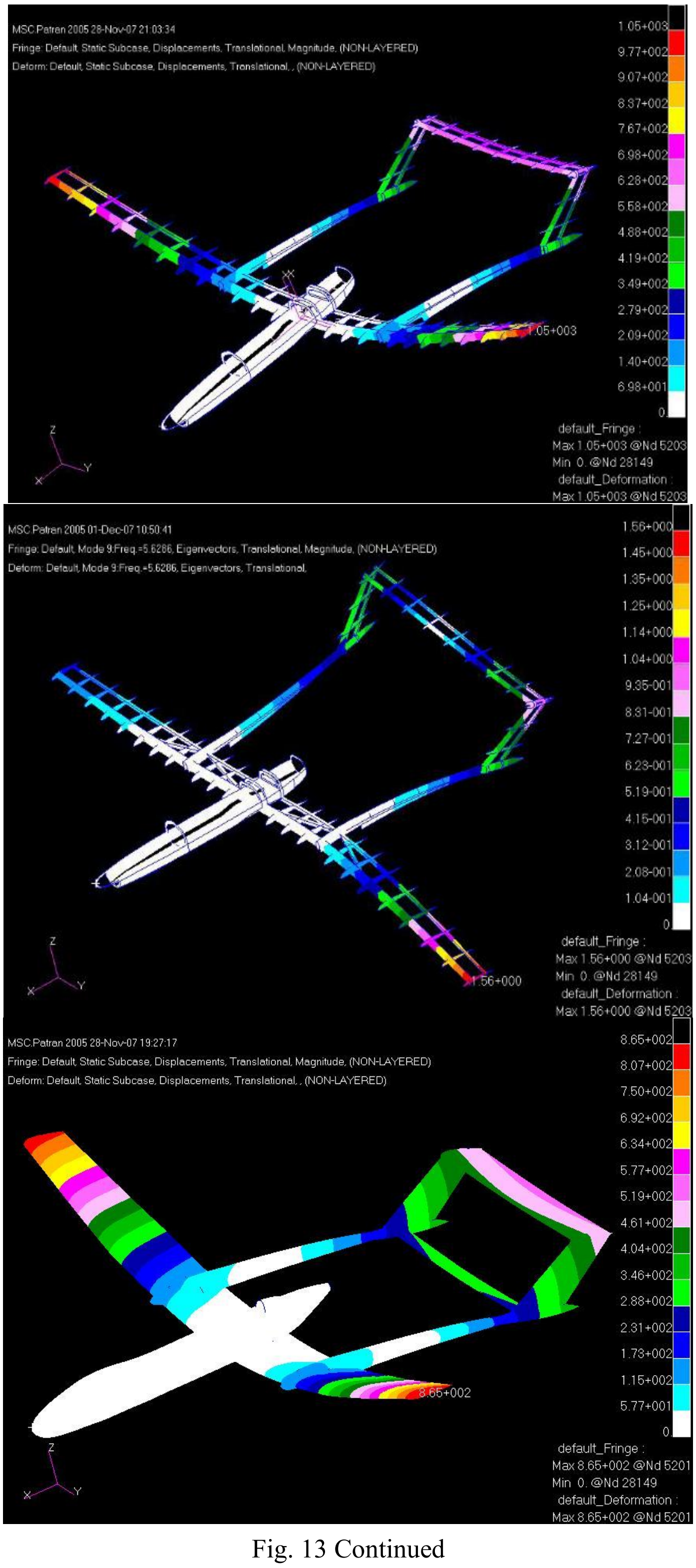

Fig. 13 Continued

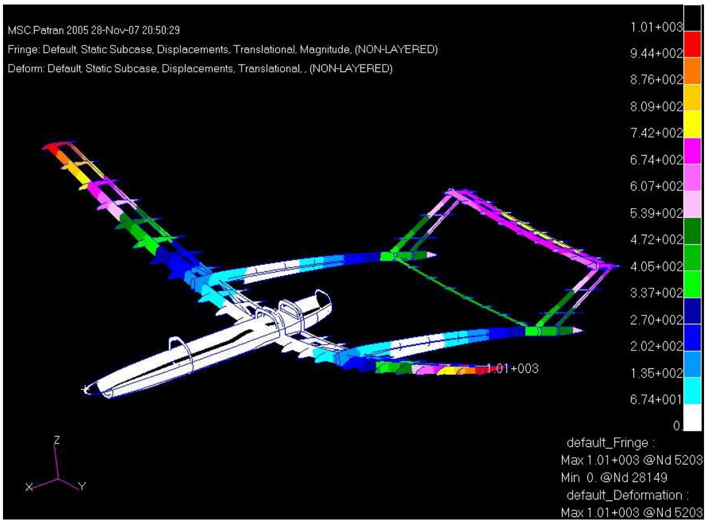

Fig. 13 Continued

Modal analysis on the configuration with a single tail plane also corroborates static analysis response in terms of displacements because of the presence of critical modes relevant to the greater twist of tail planes. This result strengthens the idea of a double tail plane solution.

To obtain a better material solution, composite materials reinforced with nanotubes are taken into account.

Carbon nanotubes (CNT) consist of long, thin cylinders of carbon. These are large macromolecules that are unique for their size, shape, and remarkable physical properties (Elastic Modulus of about 1 TPa, Maximum tensile strength of about 30 GPa) They can be thought of as a sheet of graphite (a hexagonal lattice of carbon) rolled into a cylinder. Currently, the physical properties are still being discovered and disputed. What makes it so difficult is that nanotubes have a very broad range of electronic, thermal, and structural properties that change depending on the different kinds of a nanotube (defined by its diameter, length, and chirality, or twist).

4. Consideration on a ToBeFlex UAV hydrogen fuel cell electric propulsion

ToBoFlex shows high potentials for a possible electric propelled version with hydrogen fuel cells. This activity is just started, and only preliminary considerations are here reported, as the supplier of the FC system has not been yet identified.

These potentials can be summarized as follow:

• Telescopic boom extension can effectively be used to a large amount to improve performance by changing significantly the weight distribution of the aircraft;

• The presence of the boom itself would guarantee an additional room to allocate additional H_2 fuel tanks.

• The wing could easily allocate additional phan, as in the "pods" aircraft by Airbus (Airbus 2021), Fig. 14, where every pod of this specific configuration is a standalone propulsion system which includes an H_2 fuel tank, H_2 fuel cell, electric motor, and propeller, plus ancillaries.

• The possibility of using more tails would easily permit the balance of the fuel consumption in various parts of the aircraft.

A ToBoFlex UAV is being developed with hydrogen fuel cell electric propulsion.

The fuel system now includes a pressurized cryogenic fuel tank, hydrogen fuel mass, hydrogen fuel cell, plus electric motor. It is heavier than the conventional hydrocarbon aircraft fuel system which includes the much simpler and lighter fuel tank and the internal combustion engine. The penalty of a heavier and larger pressurized fuel tank kept at cryogenic temperatures is only partially compensated by the electric motor, having a reduced weight vs. the conventional internal combustion engine.

The empty aircraft weight increases with the hydrogen fuel cell electric propulsion option. The penalty is however reduced when the aircraft is fully loaded with fuel, as hydrogen has a better energy density per unit mass than traditional conventional aircraft fuel. Hydrogen has a lower heating value (LHV) of 120 MJ/kg. The LHV for hydrocarbon aviation fuels depends on their specific composition, being 44.65 MJ/kg for Avgas 80, or 43.15 MJ/kg for Jet-A1 or Jet-TS1.

A ToboFlex UAV with an electric propeller works much better with a hydrogen fuel cell to store energy rather than a lithium-ion battery, as also acknowledged in (Hepperle 2012), which compares battery and fuel cell electric aircraft propulsion, albeit with a bias towards the battery solution.

In a battery-powered turboprop, by taking the controller efficiency η_c=98%, electric motor efficiency η_m=73%, gearbox efficiency η_g=98% and propeller efficiency η_p=80%, the total efficiency is η=73% chemical energy in the battery to propulsive energy. With a fuel cell of efficiency η_{fc}=60%, and the other efficiencies unaltered, the total efficiency is η=44%, starting from the hydrogen fuel chemical energy.

As hydrogen has an LHV of 120 MJ/kg, this corresponds to an energy density of 33,333 Wh/kg. Since η_{fc}=60%, with hydrogen fuel cells, electricity is made available to the electric motors powering the propeller with a density of 20,000 Wh/kg.

Lithium-Ion batteries have now an energy density of only 50-220 Wh/kg. This is a huge difference.

Hepperle (2012) also considers hypothetical future batteries with better energy density per unit mass, such as Zn-air, Li-S, or Li-O_2, of up to 1,750 Wh/kg.

In the case of hydrogen fuel cells, the weight of the fuel tank, which must be cryogenic pressurized, as well as the weight of the fuel cell, must be included in the picture for a fair comparison with Lithium-Ion batteries. This partially reduces the advantages of the hydrogen fuel cell solution.

However, it must be mentioned that for the long life of the battery, batteries are never used from 100% to 0% of their state of charge, but usually much less than that, typically 60-70%. This further penalizes the Lithium-Ion batteries solution.

As an additional advantage of fuel cells, the weight of the hydrogen fuel reduces as soon as the fuel is consumed. Opposite, the weight of the battery does not change with the depletion.

Finally, if battery technologies are being improved, the same is true for hydrogen fuel cells technologies, see for example (green car congress 2021a) and (green car congress 2021b). This means more power and energy per unit weight of the hydrogen fuel cell system.

Thus, the weight advantage of hydrogen fuel cells vs. batteries remains substantial, however, both technologies are expected to dramatically improve soon depending on the investments that will be made in these technologies.

Optimistically (for the battery-electric aircraft, as the actual usable energy of the battery is less than the nominal, and better energy density batteries are not yet affordable products), (Hepperle 2012) compute for a sample aircraft considered, an all-inclusive energy density of 662 Wh/kg for

Fig. 14 Fuel cell “pods” propeller aircraft. Courtesy Airbus

hydrogen fuel cells, and 180 Wh/kg for batteries.

Regarding the design of Fig. 14, the Airbus “pods” propellers (Airbus 2021) have further advantages vs. conventional fuel cell systems.

The innovative pod approach of Fig. 14 consists of multiple eight-bladed hydrogen-fuel-cell-powered “pods” mounted underneath the aircraft wing.

As previously written, each pod is a stand-alone propeller propulsion system comprising a propeller, electric motor, fuel cells, power electronics, the liquid pressurized hydrogen tank, cooling system, and a set of auxiliary equipment. This facilitates maintenance as well as refueling, which is a weak aspect of using cryogenic pressurized hydrogen.

An important feature of the pod configuration it is removable. The pod can be disassembled and reassembled quickly provide a rapid solution for maintenance and potentially hydrogen refueling (Airbus 2021).

The configuration being comprises one pusher propeller at the end of the aircraft plus two tractor propellers along with the wings, all of the pod design.

If we consider the power system of a production Toyota Mirai fuel cell (FC) car (Argonne National Laboratory 2017, Lohse-Busch *et al.* 2018), hydrogen is stored in purpose-built tanks and it is then released to the fuel cell system, where hydrogen and oxygen are combined to produce electricity and water vapor. The first generation (2014 to 2020) had an electric motor fuel cell-powered 113 kW and 335 Nm. Electricity generation efficiency has been enhanced through the use of 3D fine mesh flow channels. These channels are arranged in a fine 3D lattice structure and enhance the dispersion of air (oxygen), thereby enabling uniform generation of electricity on cell surfaces. The stack's power output density is 3.1 kW/L or 2.0 kW/kg. Each stack comprises 370 (single-line stacking) cells, with a cell thickness of 1.34 mm and a weight of 102 g. The Toyota Mirai has two hydrogen tanks with a three-layer structure made of carbon-fiber-reinforced plastic. The tanks are 122 liters combined. They store hydrogen at 70 MPa. The tanks have a combined weight of 87.5 kg and 5 kg of hydrogen capacity. This production hydrogen-powered fuel cell vehicle had an FC stack peak efficiency of 66%, and an FC System peak efficiency of 63%.

While the availability of purpose-built tanks and FC systems may certainly help improve performances, the use of FC systems repurposed from other applications may also be considered.

5. Conclusions

This paper proposes an innovative architecture for UAV planes to augment efficiency and widen the operational scenario. A hydrogen fuel cell electric propulsion system is presently being considered for the deployment of this UAV in a net-zero application. As the supplier of the complete fuel cell system and the electric propeller has not been individuated yet, uncertainties still exist in the actual definition of the propulsion system, and results are only provided for the aircraft design.

For the current model, the Telescopic Tail Boom permits obtaining an optimum attitude of flight for a longer time and a longer endurance. This is a considerable solution in extreme loading conditions, for example when a high payload is concentrated on the prow. In general, the structure is rigid and strong. The fuel mass permits alleviating the wing structure loads.

By observing the configuration with the single tail plane, in extreme flight conditions is possible to detect a Tail Plane warping that could trouble the Tail Plane functionality. The problem could be resolved by putting a second horizontal Tail Plane. It is demonstrated that the introduction of a second Tail Plane removes the warping effect.

The presence of the oblique longeron doesn’t provide any relevant effect. In extreme flight conditions is possible to observe a Tail Plane warping that could affect the Tail Plane functionality. The problem could be resolved by putting a second horizontal Tail Plane. The analysis results show that the introduction of a second Tail Plane removes the warping effect.

The hydrogen fuel cell electric propulsion is in progress because it is necessary to optimize all technological aspects to succeed. It is important to push together all areas of the whole ELOTAC project to get a system that will work. The challenge can be seen in two parts: first, finding the best balance between weight and efficiency, and then making the entire thing as reliable as possible, especially considering the UAV all-compound materials structure and hydrogen fuel cell electric propeller management system. This activity will necessitate a supplier of the propulsion system the team will integrate with the aircraft design.

References

Airbus (2021), Hydrogen-Pod-Configuration; Airbus, Leiden, Netherlands. www.airbus.com/newsroom/stories/hydrogen-pod-configuration.html.

Arat, H.T., Sürer, M.G., Gökpinar, S. and Aydin, K. (2020), “Conceptual design analysis for a lightweight aircraft with a fuel cell hybrid propulsion system”, *Energy Sour., Part A: Recov. Utiliz. Environ. Effect.*, 1-15. https://doi.org/10.1080/15567036.2020.1773966.

Argonne National Laboratory (2017), Energy Systems D3 2016 Toyota Mirai. www.anl.gov/es/energy-systems-d3-2016-toyota-mirai.

Baroutaji, A., Wilberforce, T., Ramadan, M. and Olabi, A.G. (2019), “Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors”, *Renew. Sustain. Energy Rev.*, **106**, 31-40. https://doi.org/10.1016/j.rser.2019.02.022.

Boretti, A. (2021), “Perspectives of cryo-compressed hydrogen aviation”, *Adv. Aircraft Spacecraft Sci.*, **8**(3), 199-211. https://doi.org/10.12989/aas.2021.8.3.199.

Bradley, T., Moffitt, B., Fuller, T., Mavris, D. and Parekh, D. (2008), “Design studies for hydrogen fuel cell powered unmanned aerial vehicles”, *6th AIAA Applied Aerodynamics Conference*, 6413. https://doi.org/10.2514/6.2008-6413.

Bradley, T.H., Moffitt, B.A., Mavris, D.N. and Parekh, D.E. (2007), “Development and experimental characterization of a fuel cell-powered aircraft”, *J. Power Sour.*, **171**(2), 793-801. https://doi.org/10.1016/j.jpowsour.2007.06.215.

Bradley, T.H., Moffitt, B.A., Thomas, R.W., Mavris, D.N. and Parekh, D.E. (2006), "Test results for a fuel cell-powered demonstration aircraft", SAE Technical Paper No. 2006-01-3092. https://doi.org/10.4271/2006-01-3092.

Brelje, B.J. and Martins, J.R. (2021), "Aerostructural wing optimization for a hydrogen fuel cell aircraft", *AIAA Scitech 2021 Forum*, 1132.

Carrera, E. and Triffiletti, S. (2009), "Structural design of ELOTAC full composite, inflatable UAV", *Proc. of International Conference UAV World*, Frankfurt, Germany.

Cummins (2021), Cummins Hydrogen Power Takes Flight; Cummins, Columbus, Indiana, United States.

Friedrich, K.A., Kallo, J., Schirmer, J. and Schmitthals, G. (2009), "Fuel cell systems for aircraft application", *ECS Trans.*, **25**(1), 193. https://doi.org/10.1149/1.3210571.

Green Car Congress (2021a), HyPoint Working with BASF New Business to Develop High-Performance Hydrogen Fuel Cell Membranes for Aviation; >3,000 W/kg; BioAge Group, LLC, Mill Valley, California, United States.

Green Car Congress (2021b), Piasecki Aircraft Partner to Deliver Next-Generation Hydrogen Fuel Cell Systems for eVTOLs; BioAge Group, LLC, Mill Valley, California, United States.

Guynn, M.D., Freh, J.E. and Olson, E.D. (2004), "Evaluation of a hydrogen fuel cell powered blended-wing-body aircraft concept for reduced noise and emissions", NASNTM-2004-2 12989 NASA Langley Research Center, Hampton, Virginia.

Hepperle, M. (2012), "Electric flight–potential and limitations", NATO/OTAN STO-MP-AVT-209.

Hydrogen Council (2021), Hydrogen-Insights-2021; Hydrogen Council, Brussels, Belgium.

Kallo, J. (2015), "DLR leads HY4 project for four-seater fuel cell aircraft", *Fuel Cell. Bull.*, **2015**(11), 13. https://doi.org/10.1016/S1464-2859(15)30362-X.

Kim, T. and Kwon, S. (2012), "Design and development of a fuel cell-powered small unmanned aircraft", *Int. J. Hydrog. Energy*, **37**(1), 615-622. https://doi.org/10.1016/j.ijhydene.2011.09.051.

Lapeña-Rey, N., Mosquera, J., Bataller, E. and Ortí, F. (2010), "First fuel-cell manned aircraft", *J. Aircraft*, **47**(6),1825-1835. https://doi.org/10.2514/1.42234.

Lohse-Busch, H., Stutenberg, K., Duoba, M. and Iliev, S., (2018), "Technology assessment of a fuel cell vehicle: 2017 Toyota Mirai (No. ANL/ESD-18/12)", Argonne National Lab, (ANL), Argonne, IL, United States.

Mul2 Research Group (2007), Millennium Sky-y.

Ng, W. and Datta, A. (2019), "Hydrogen fuel cells and batteries for electric-vertical takeoff and landing aircraft", *J. Aircraft*, **56**(5), 1765-1782. https://doi.org/10.2514/1.C035218.

Oh, T.H. (2018), "Conceptual design of small unmanned aerial vehicle with proton exchange membrane fuel cell system for long endurance mission", *Energy Convers. Manage.*, **176**, 349-356. https://doi.org/101016/jenconman201809036.

Özbek, E., Yalin, G., Ekici, S. and Karakoc, T.H. (2020), "Evaluation of design methodology, limitations, and iterations of a hydrogen fuelled hybrid fuel cell mini UAV", *Energy*, **213**, 118757. https://doi.org/10.1016/j.energy.2020.118757.

AP