Design and sizing of an airship supported by CAE

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Abstract

This paper describes research activities that were undertaken for the design of an airship using hydrogen as lifting gas. Even if the final airship should be able to transport a 40 tons container, the first phase of the project was dedicated to the design and sizing of a smaller demonstrator of about 16m long that will show all the technical difficulties that will be encountered on the final structure of larger size. The paper explains the design concepts and illustrates how finite elements and structural optimization were used to support the sizing of the airship structural components.

1. Introduction

Over the last 20 years, there has been a renewed interest in airship technology, as it can be seen on the internet with lots of technical reports, scientific papers and (sometimes) success stories. Innovative airships have been designed not only for military but also for civil and freight applications.

In this context, a research team was set up in Wallonia (Belgium), headed by the Flywin Company, in order to work on the possibility to design and manufacture an unmanned airship, using hydrogen as lifting gas, that could transport 40 tons containers, for overseas freight. Before starting working on a structure that could measure 150m long and because of storage limitations (unavailability of a large hangar), the idea was to train with a smaller demonstrator of about 16m long and a diameter of 4m, that would cover (almost) all the scientific and technical challenges and difficulties that could be encountered with the final application.

The partners of the consortium (Flywin, GDTech, Deltatec, Université Catholique de Louvain and Université Libre de Bruxelles) had then to start working on different disciplines like aerostatics, aerodynamics, flight dynamics and control, propulsion, structure and weight, and iterate on the solution.

This paper highlights the different steps that have been taken in the project for the genesis of the concept and of the structural design, and for its implementation supported by CAE. Two main challenges had to be dealt with: gas management and structural weight.

Seeing the dimensions of our demonstrator, a maximum volume of about 130m^3 for the envelope was possible. This provided an upper bound on the airship total weight of 130 kg, including the structure itself, the envelope membrane, the tail planes, the batteries and electric cables, the engines and the propulsion systems (no payload).

Starting from the idea of a semi-rigid solution, the design finally moved to a rigid structure.

Semi-rigid airships have some form of supporting structure, but the external envelope shape is maintained by internal pressure. They use ballonets to keep the pressure balance between the inside lifting gas and the outside air during ascents and descents. This together with the management of hydrogen was considered as a big issue. Anyway, before giving up this solution, structural analysis was conducted and the finite element modeling was adapted to define the right pressure distribution that provides the buoyancy of the airship on the external envelope.

On the other side, in a rigid airship the lifting gas is contained in one or more internal gasbags, what is easier to manage. However, a rigid airship has got a structural framework that maintains the external shape and carries all the structural loads. Seeing the strong restriction on weight, designing and sizing this structural framework and the tail planes then became a real challenge that would provide the smaller rigid airship ever designed and manufactured in the world. In this paper, it is explained how the structural topology of the frame was selected and how composite materials and additive-manufactured plastic connections were sized based on non-linear finite element analysis and structural optimization techniques. It is illustrated how simulation was used to size the tail planes, to design power transmission components, and validate the solution when submitted to its own weight in a buoyancy scenario and in flight, with wind gusts.

2. Types of airships

There exist three types of airship constructions: blimp, semi-rigid and fully-rigid concepts (Figure 1). In a blimp, there is no internal structure. The external membrane is filled with lifting gas to provide the external shape. Cables can be distributed around the airship in order to attach a payload at the bottom of the structure. They use ballonets to keep the pressure balance between the inside lifting gas and the outside air during ascents and descents. Semi-rigid airships have some form of supporting structure usually composed of a keel and a truss structure, but the external envelope shape is maintained by internal pressure in the lifting gas. They use ballonets with air to keep the pressure balance between the inside lifting gas and the outside air during ascents and descents manoeuvers. In a rigid airship, the lifting gas is contained in one or more internal gasbags, which is easier to manage. A rigid airship has got a structural framework that maintains the external shape and carries all the structural loads. Because of the use of a full structure, this kind of airship is clearly heavier than the two other configurations, but is relevant for the design of very large airships that can work with heavy pay-loads.

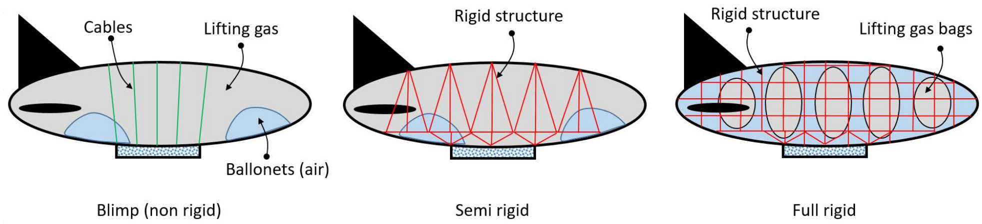

Figure 1: Three types of airship constructions, ballonets and gas bags

Since the ultimate goal is to develop a large airship able to transport a heavy payload, the blimp solution was directly rejected. It was therefore decided to work on a prototype of reduced size, either based on a semi-rigid or a fully rigid solution. Even if a rigid solution was finally selected, research activities and results for the semi-rigid solution are also presented in the next sections.

3. Specifications

The goal of the Structure part of the project is to design and size the structure of an airship that can accommodate about 130 m³ of hydrogen. This limitation corresponds to the volume of an ellipsoidal airship (16 x 4 x 4 m³) that can be stored in the laboratory hall of Université Catholique de Louvain.

4. Design activities: semi-rigid concept

The buoyancy force is equal to the weight of displaced fluid, when a body is immersed in the fluid. Considering a volume V filled with a gas of density ρ_g, the acceleration of the gravity g, and the density of the ambient air ρ_a, the buoyancy force is given by:

$$B = (\rho_a - \rho_g)gV \tag{1}$$

For information, the density of the air (at see level) is equal to 1.2 kg/m³ and the density of the gas (hydrogen) is taken as 0.09 kg/m³. This vertical force *B*, which provides the lift on the body, is applied at the centroid of the displaced surrounding fluid. As depicted in Figure 2a and 2b, *B* can be seen as the resultant of a pressure distribution on the envelope of the body immersed in the fluid. Let's imagine that at location *L* (Figure 2a), the pressure *P* of the internal gas is equal to the pressure of the air. At point U, the value of the pressures is given by:

$$P_U^a = P_L^a - \rho_a g h$$

$$P_U^g = P_L^g - \rho_g g h$$

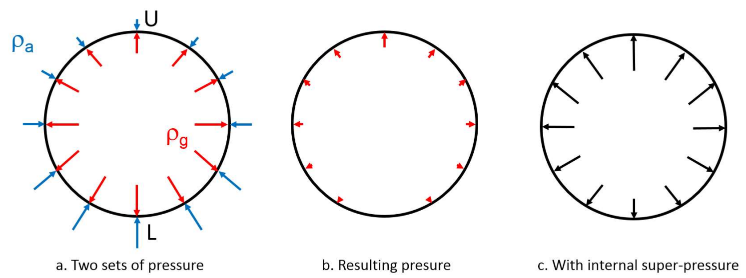

Figure 2: Distribution of pressure from the buoyancy

where h is the height of the body (diameter of the circular section in Figure 2). As $P_L^g = P_L^a$ and $\rho_a > \rho_g$, it comes that:

$$P_U^g > P_U^a$$

This difference in the pressures provides the lift, which is actually the buoyancy force. In this calculation, the variation of the densities with respect to the height is neglected, as it is clearly a second order effect. In the frame of a blimp or a semi-rigid airship, the shape of the envelope is maintained by an internal overpressure, called super-pressure. This super-pressure also contributes to insure the structural integrity of the envelope during the flight (no geometrical collapse). In practice, a value of around 600 Pa is used. It means that this internal super-pressure must be added to the effects depicted in Figure 2b, the result being illustrated in Figure 2c. This super-pressure will not influence the value of the resulting buoyancy force. As using the resulting buoyancy force *B* would lead to loss of important information about the loading and its effect on the envelop, the pressure distribution of Figure 2c must then be defined in the finite element model of the airship. A specific FORTRAN program has been developed in order to define a regular mesh of the airship. This mesh is written in SAMCEF format (Siemens PLM software). Here, the airship envelope is built with two half ellipsoids. The user of the FORTRAN program has a full control on the dimensions and on the mesh density, which is controlled by the number of elements defined in the longitudinal and circumferential directions. The FORTRAN program also computes the values of the pressure, with its distribution along the height (Figure 3).

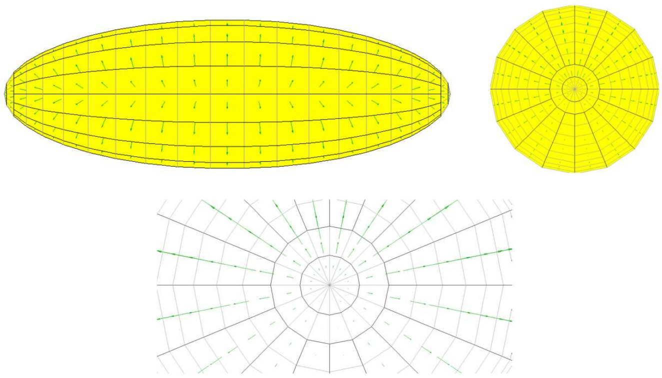

Figure 3: Pressure distribution for a given resulting buoyany

Comparison between analytical and numerical solutions was conducted in order to validate the FEM model. In Figure 4, the distribution of the circumferential stress obtained with FEM is compared to the analytical value $\sigma_\theta = Pr/t$.

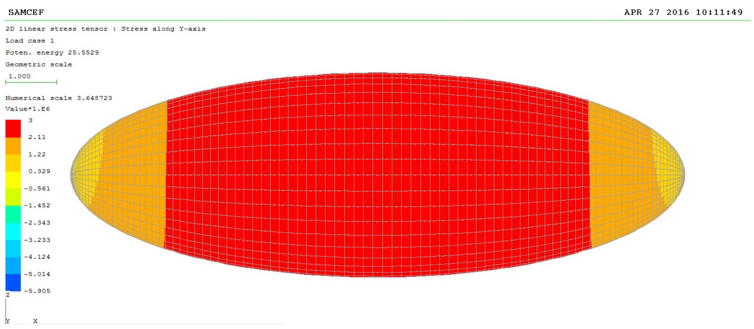

Figure 4: Internal pressure only => $\sigma_{\theta max}$ around 3MPa

After a meeting with the father of the Zeppelin semi-rigid solution, it was decided to given up a semi-rigid solution and to move to a full rigid construction, since the management of the lifting gas was confirmed safer and easier with this kind of airship construction. We then stopped our investigations on the semi-rigid model and started working on a fully rigid design.

5. Design activities: fully-rigid concept

It appeared that the smallest rigid airship reported in the literature [2] has got a volume of 8500m³, what is far above the targeted 130m³ of our project. This was one of the challenges of the project: design the fully rigid structure of a very small airship, with a very stringent constraint on the weight, while keeping acceptable stiffness and strength performances.

When a rigid airship is studied, the external envelope is no more inflated and doesn't support any membrane loads. Its thickness is therefore much smaller than the one of a semi-rigid airship. The main contribution to the weight comes from the truss structure which is used to define the shape of the external envelope. Having a look at the existing solutions (like the Zeppelin of the last century), it came that the internal structure should be made of bars or beams connected together to create longitudinal stiffeners (kinds of spars or stringers) and frames, like in an aircraft fuselage. Besides these structural elements, additional bars can also be defined at the bottom of the structure (where the pay-load may be placed). Moreover, cables are also often used, either to stiffen the truss structure in contact with the external envelop (to create a bracing structure, like an isogrid structure) or to improve the rigidity of the cross section at the frames location. It was found that using these cables is important in order to improve the stiffness of the airship.

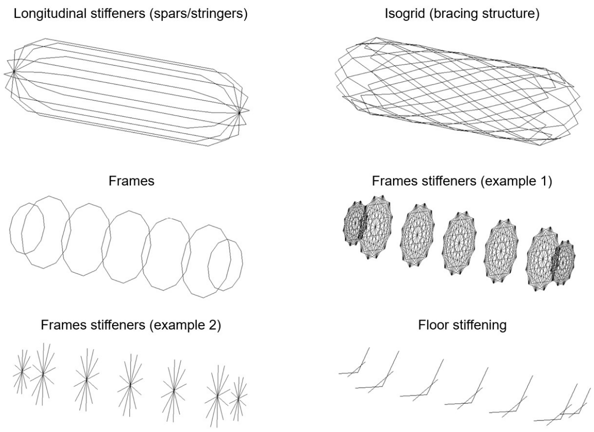

Figure 5: Details of the components of the airship

A FORTRAN program is developed to define easily and automatically the internal truss-like structure composing the rigid airship (Figure 5). This tool was found essential to make a quick trade-off between different possible solutions. The number of frames can be parameterized, as well as the number of longitudinal stiffeners. Waiting for new inputs from the aerodynamic requirements, we started from the principle that the airship would be made of two half-spherical parts connected by a cylinder. The idea here was to try to determine very quickly whether a fully-rigid solution with a so small volume was viable. Trade-off studies were then conducted, changing the number of frames, longitudinal stiffeners … Buoyancy load and self-weight were considered. An illustration is given in Figure 6, with a nacelle and engines modelled with concentrated masses. It was concluded that a solution was possible, and the investigations on the design and sizing continued.

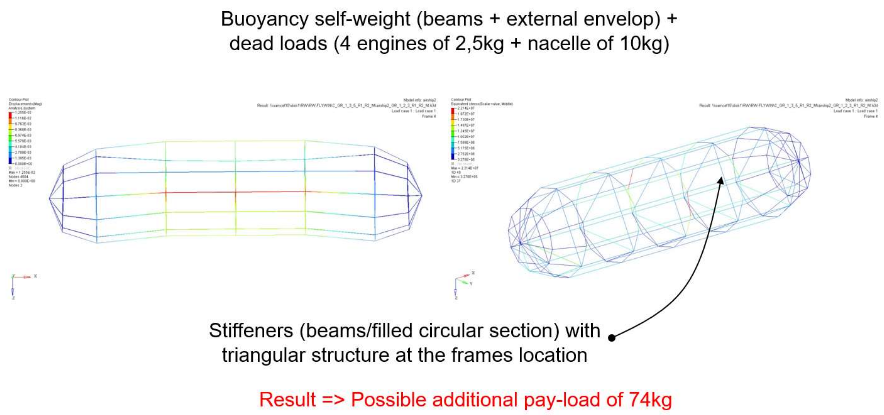

Figure 6: Detailled model with 7 frames, L = 15m and volume is 155m³; triangle stiffeners structure at frames of the components of the airship

Seeing these large restrictions on weight, it was decided to use cylindrical bars with a hollow section made up of carbon-epoxy material, with continuous fibers and a specific stacking sequence that provides a good stiffness in tension, compression and bending. A new external shape was suggested by the aerodynamicists: it is composed of 2 semi-ellipsoids separated by a cylindrical par (Figure 7). This constitutes the final shape of the airship.

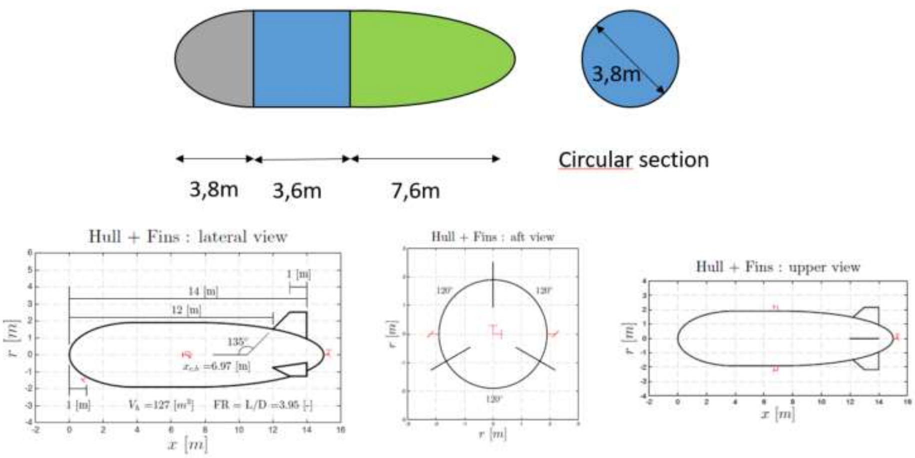

Figure 7: New dimensions and definition of the empennage

Another important point is that an additional load case was included in the problem: the bending moment coming from gust. According to Carichner and Nicolai (AIAA 2013), and TAR (Transport Airship Requirements 2000), the maximum bending moment in flight due to gust (in ft-lb) is given by:

$$M = 0.029V\left(\frac{L}{2}\right)^{0.25}[1 + (FR - 4)(0.5624L^{0.02} - 0.5)]\rho v U_m$$

It was decided to include the empennage and the engine weights in the model. Seeing the large effort needed to try to determine manually an optimal solution, topology optimization was then used to speed up the design process. The FORTRAN program was used to generate structural universes made of lots of bars that serve as initial solution for topology optimization runs. Topology optimization will then "remove" some of these bars to get a solution satisfying requirements. The TOPOL software (Siemens PLM) was used, together with the SAMCEF solver. Three load cases were considered: 1/ self-weigth, 2/ buoyancy plus self-weight, 3/ self-weigth, buoyancy plus self-weight plus gust moment. The objective function was to minimize the compliance (maximize the stiffness), while satisfying a restriction on the total mass. The models include the empennage and the engines, modeled like concentrated masses. The cables are not taken into account, since linear analysis only is possible with TOPOL.

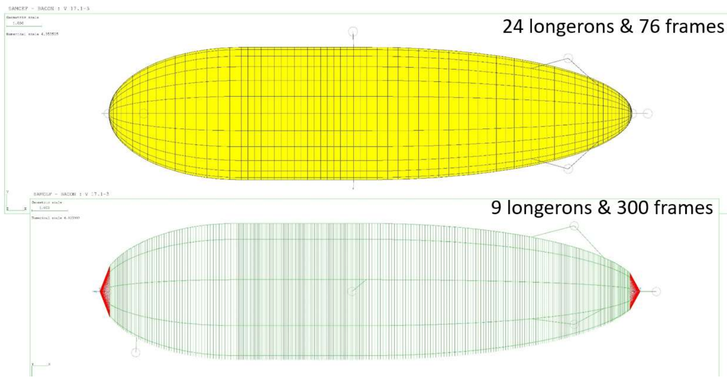

Figure 8: Examples of structural universes as initial guess for topology optimization

The solution is provided in the Figure below. We see that 9 frames remain in the solution, and that 6 longitudinal stiffeners are enough to satisfy the design criteria

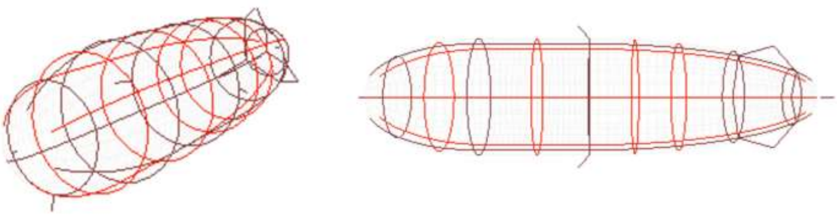

Figure 9: Result of topology optimization

Using 6 longerons was found too small when volume of hydrogen is concerned. Indeed, working with a so small number of longitudinal stiffener will provide an external cross-section shape that is far from the one of a circle, therefore loosing volume for the lifting gas. It was decided with the aerodynamicists to use 9 longerons, with a flat surface at the bottom, what is also a good solution for the assembly of the empennage whom the elements are at an angle of 120° to each other (See Figure 7). FEM validations were conducted on the new design, in static and dynamic analyses, including the cables and the 3 load cases, as illustrated below. This provided the stresses and the forces in the structural members, as well as an idea about the global stiffness of the solution.

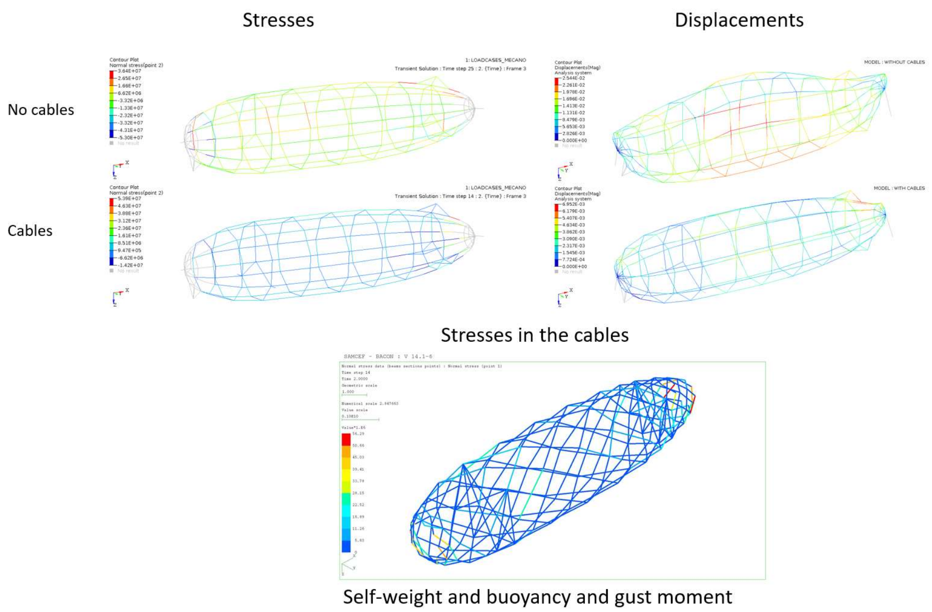

Figure 10: FEM validation of the optimal solution

In parallel to all the FEM computations, an EXCEL sheet was developed to report the dimensions and weights of the different elements making the airship. This sheet was important to check the total weight and the location of the center of gravity (a right position of the g.c. being essential for the maneuverability of the airship).

6. Design and sizing of components

In order to connect the composite bars together, plastic connections are used. Using plastic with carbon bars will avoid galvanic corrosion between aluminium and carbon. Seeing the very specific application, these plastic connections were designed during the project. Because of their possible complex shapes and since we are not in the context of a massive production, 3D-printing was used to manufacture the connections. The strength of the different designs was validated by physical testing (clearly with non standard procedures), and with the finite element approach.

Figure 11: Validation of the connections

The empennage were made of foam (PU – poly-urethane) with a structure using carbon tubes. The design was also validated with finite elements, regarding stiffness and strength.

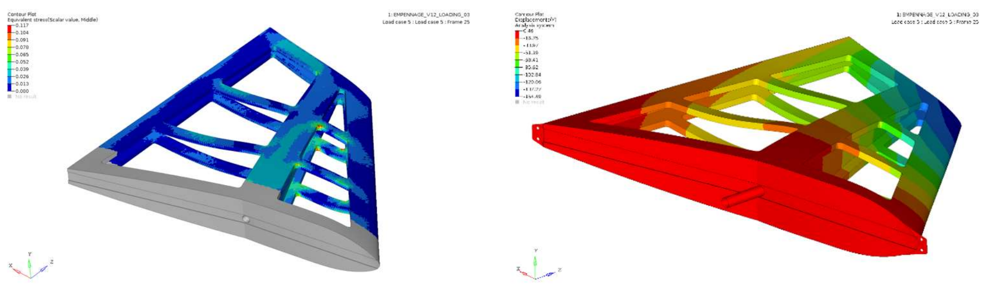

Figure 12: Validation of the empennages

Elements used to transmit the torque from the servo-motors to the control surfaces were also designed and validated with the finite element method.

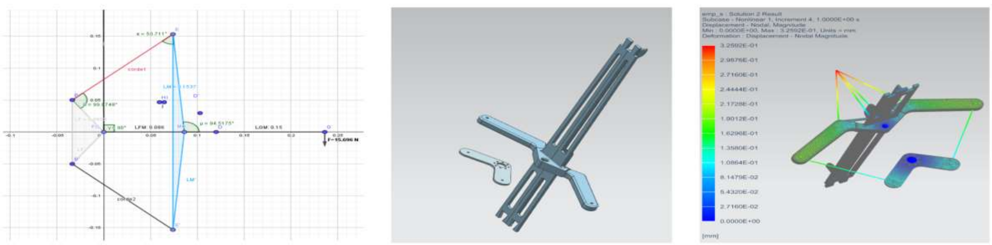

Figure 13: Validation of torque transmitter device for the control surfaces

7. Final solution and flight tests

The final design of the airship is presented in Figure 14.

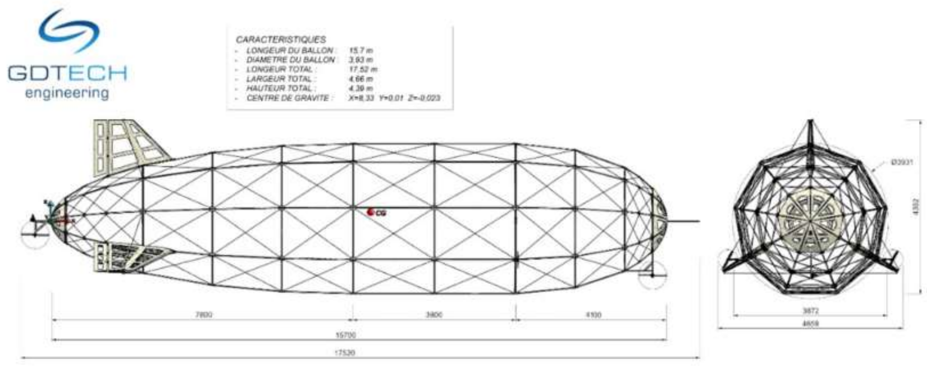

Figure 14: Final design of the airship

The following Figures illustrate the final structure, as well as the airship floating thanks to the lifting gas.

Figure 15: Assembled and floating airship

8. Conclusions and future work

This paper briefly described the work done over 2 years to design and size an aircraft, working with hydrogen as lifting gas, and having a volume of about 130m³. The presented solution is the smallest rigid airship ever designed. This was possible thanks to the use of CAE (finite elements analysis and structural optimization). Flight tests, with working propulsion system, are planned in Spring 2019.

9. Acknowledgements

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