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Mechanical Design of an Innovative Method for CNG Transporting over Long Distances: Logistics, Executive and Operative Aspects

Gianluca Capitta, Lorenzo Damiani, Stefano Laudani, Roberto Revetria, Emanuele Morra

***Abstract*— The present paper shows the main aspects related to the conceptual design of an innovative mean of transport for natural gas. The analysis inspects the features and the overall calculation of a pilot scale (7.5 m length)airship drone prototype, able to carry out natural gas transport, contained in impermeable bags, between two pre-established stations of departure and arrival, in accordance with the ENAC regulations. The proposed drone vehicle envisages the implementation of innovative solutions both for motion (such as the remote control, the thermal and electric propulsion) and for materials employed.**

***Index Terms* — Natural gas transport; drone airship; Logistics, Conceptual Design.**

I. Introduction

Traditional technologies, used to transport gas from the extraction well to storage sites and utilities, are based on the use of ships and pipelines. The traditional transportation means require either a gas compression or a gas liquefying, which are very energy expensive.

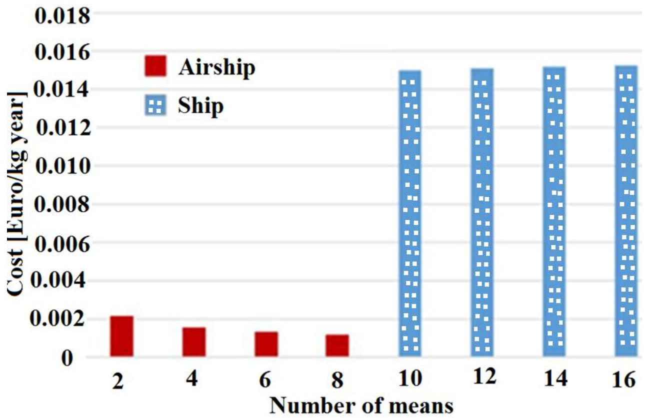

Fig. 1. Cost comparison LTA-CNG [2].

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G. Capitta is a student of the University of Genoa, Liguria, Italy (phone: 3479633414; e-mail: gianlu93@fastwebnet.it).

L. Damiani is an associate researcher at Genoa University (phone +393489194710, e-mail Lorenzo.Damiani@unige.it).

S. Laudani is a student of the University of Genoa, Liguria, Italy (phone: 3334345640; e-mail: laudani.stefano@gmail.com).

R. Revetria (Corresponding author) is an engineer and a professor with University of Genoa, Liguria, Italy (phone: 3339874234; e-mail: r_revetria@hotmail.com)

E. Morra is a freelancer engineer of Turin, Piemonte, Italy (phone: 3391505847; e-mail: e.morra@hotmail.it)

To obviate this need, which involves a considerable financial outflow, the authors proposed to employ a drone airship [1], whose transportation costs were calculated to be very lower than the traditional ship in a previous work [2, 3].

The mean identified in order to accomplish the mission in question is a Lighter Than Air (LTA) drone airship of modern design. Such vehicle presents different features with respect to the traditional ones, and takes the name of “hybrid”, as it presents aeronautical wings and a double-prolate ellipsoid form. The principle of operation is based on the Archimedes’ thrust provided by the lifting gas that can be helium or hydrogen.

Although hydrogen produces upward thrusts more than 10% compared to helium and costs less, the choice fell on the latter because it is an inert gas. Gases are stored into the airship in impermeable gas bags. To carry out the procedure of loading and downloading, it made a reference to the group of industry reduction of first and second stage. This solution allows to avoid the phase of gas compression, as such the fluid undergoes a double expansion. Finally it shows the ENAC normative (Ente Nazionale Aviazione Civile), linked to this operations typology and it analyses the main emergency sceneries with possible relative solutions to solve it.

II. Prototype drone design

The target of the study is to determine the minimum size to be attributed to the blimp in order to produce a pilot prototype. The natural gas to helium ratio was established as 60% - 40%. It is required to provide an oversized number of helium gas bags to prevent from any unforeseen event. To obtain a valid sizing, reference was made to the expression that describes the Archimedes’ principle (Eq. 1).

$$S = V_{He}(\rho_{air} - \rho_{He}) \quad (1)$$

Where:

- S is the flotation thrust, expressed in kg;
- V_{He} is the transported helium volume, expressed in m^3;
- ρ_{air} is the air density at cruising altitude, expressed in kg/m^3;
- ρ_{He} is the helium density, expressed in kg/m^3.

The helium volume is closely related to the size of the airship, therefore, an iterative procedure was adopted with the aim of obtaining a flotation thrust greater than the total weight of the mean. In this way it has been identified the

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size of a single ellipsoid: greater drive shaft of 7.5 m and lower drive shafts of 2.5 m (Fig. 2.).

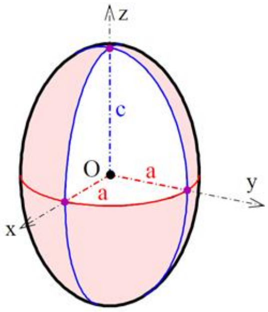

Fig. 2. Prolate ellipsoid: the two lower drive shafts have equal length.

III. Material analysis

For the realization of the airship, different types of materials were chosen.

The internal structure is made of composite material, the Artboard / Recore, a phenolic resin foam reinforced with glass fibers. It presents important properties including light weight, high stiffness, ease of bonding and traction, wear, vibration and fire strength. For the sizing of the frame the theory of A. R. Bryant has been considered concerning the internal structure of submarines, for the similarity with the airships. Considering a single ellipsoid, the frame is composed of fourteen coaxial and equidistant rings having an "I" transversal section; the annular profiles are connected via strips and follow the ellipsoid line. Moreover, with the same method, the two ellipsoid structures are joined through a link involving the four central rings (Fig. 3.)

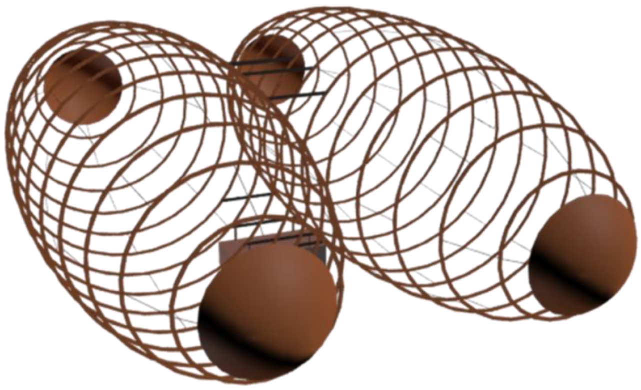

Fig. 3. Structure prospect.

Glued on the shell, there is a polyurethane casing, whose main characteristics are lower thickness and density, lightness and resistance to mechanical stresses and to the action of ultraviolet rays. Its functions are to secure an aerodynamic shape to the mean and to protect the inner part.

Moreover, for safety reasons, the possibility that a lightning can strike the airship was considered; Owing to the flammability characteristics of natural gas contained in the casing, a lightning would act as an ignition source for the fuel. Therefore it has been decided to realize an aluminum Faraday cage. Aluminum was chosen for its excellent electrical conductivity. In particular it has been suggested to use a 50x50 mm aluminum net realized with 3 mm diameter wires.

For the gas bags material, the bi-axially oriented polyethylene terephthalate was identified, a plastic material of polyester family. The most important features of this material are the reduced density, the possibility to obtain very thin films (also 20µm) and the impermeability to gases. Commercially, gas bags in this material are available, with maximum capacity of 50 litres, therefore it is necessary to realize elliptical custom made bags in order to efficiently exploit the available volume and significantly reduce the weight (Fig. 4.).

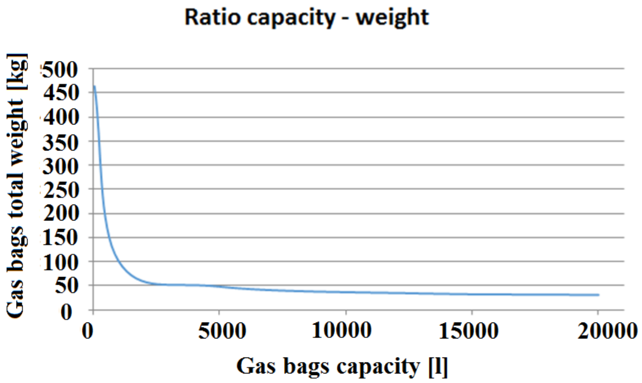

Fig. 4. Graph representing the relationship between the capacity of a single bag and the total weight.

The choice fell on 13 cubic meters capacity gas bags with 7.5 meters length and minor semi-axes equal to 1 meter. This solution involves a number 12 gas bags for the helium storage; for safety reasons, the number of 12 gas bags is redundant, since the lift force is assured by the correct operation of only 10 out of 12 bags. Instead, the number of gas bags that contain natural gas is equal to 16.

IV. Propulsion

The airship motion is assured by three propellers [4], of which one produces the thrust for propulsion and the two other act as thrusters and operate in maneuvering operations. The powertrain scheme [5, 6] is provided in Fig. 5. The internal combustion engine (of the “hot plug” typology) moves an alternator and, by means of the same shaft, the main propeller. The two thrusters, moved by brushless electric motors, take power from the alternator.

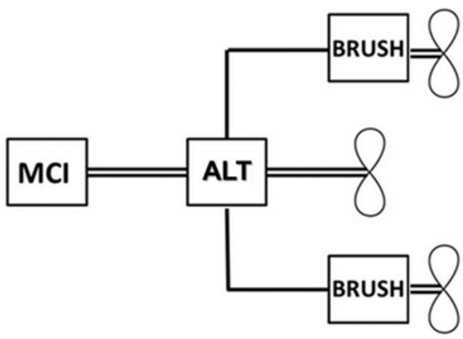

Fig. 5. Propulsion powertrain.

Brushless motors, although mainly restricted to medium-low powers (≤ 50 kW), have numerous advantages: reduced maintenance, great reliability, good performance, easy heat

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removal, high power/mass and power/size ratios, low acoustic noise and no need of special start devices.

The propeller, thanks to the rotary movement transmitted by the drive shaft, rotates at a speed such as to propel the air flow backwards for allowing the airship to proceed forward. The propeller is therefore the organ employed to accelerate the drive up to the flight speed and to win the aerodynamic resistance which opposes to the motion.

For the realization of this project it has been opted for the use of two-bladed propellers, the most appropriate for low engine output powers. Propellers are made of carbon fibers, which combine mechanical resistance and low weight; moreover, the propellers provide fixed geometry because great performance is not demanded. For the sizing of the internal combustion engine it is necessary to calculate the force necessary to overcome the drag exerted on the vehicle in motion (Eq. 2).

$$F_R = \tfrac{1}{2}\, \rho_{\text{air}}\, C_x\, A\, v^2\, k \qquad (2)$$

Where:

- F_R is the drag force expressed in N;
- ρ_{air} is the air density at cruising altitude (900 m), expressed in kg/m^3;
- C_x is the drag coefficient;
- A is the front area of the airship;
- v is the speed of the airship (40 km/h), expressed in m/s;
- k is a safety factor assumed to be 2.

F_R is the force required by the propulsion propeller to move the airship at the set speed.

To size the propeller diameter, reference was made to the actuator disk theory developed by Rankine; it is considered a steady stream, not viscous, incompressible and asymptotic V∞ speed investing perpendicularly a circular area of infinitesimal thickness and diameter D (Fig. 6).

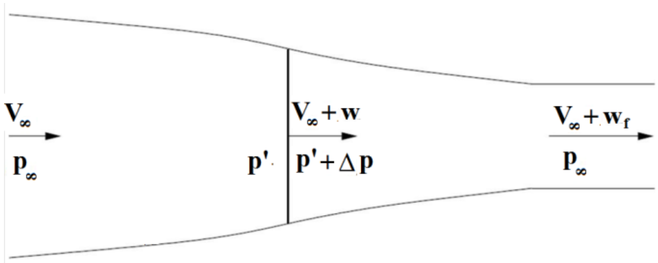

Fig. 6. Flow tube by the propeller.

It is assumed that the physical quantities in the flow tube are only a function of the axial coordinate z. It is possible to notice that speed increases along the z axis. In correspondence of the propeller axial coordinate, the speed is increased by a quantity of w, corresponding to 40% of the upstream speed; downstream instead speed appears to be increased by 80%. It is also assumed that the disk does not introduce a tangential speed component in the flow. With these assumptions, it is possible to obtain the propeller diameter necessary to sustain the airship at the speed set in the design phase (Eq. 3).

$$D = \sqrt{\frac{2\, F_R}{\pi\, \rho\, (V_\infty + w)\, w}} \qquad (3)$$

Where:

- D is the propeller diameter, expressed in meters;
- F_R is the force of the propeller, expressed in N;
- ρ is the air density at cruising altitude (900 m), expressed in kg/m^3;
- $V\infty$ is the airship speed expressed in m/s;
- w is the speed increase by the propeller .

The application of the above exposed theory lead to a propeller diameter equal to 90 cm.

Then the power P associated to the propeller exerting on the airflow a force F_R has been found resolving the equation (Eq. 4)

$$P = [(V\infty + w)\, F_R] \,/\, 1000 \qquad (4)$$

Where:

- P is the power required by the propeller, expressed in kW;
- 1000 is a conversion factor.

It is therefore possible to estimate the propeller efficiency by making the ratio between the power useful for motion (equal to the product between the propulsion force F_R and the vehicle speed $V\infty$) and the propeller power (Eq. 5).

$$\eta = (F_R\, V\infty) \,/\, P = 1 \,/\, (1 + a) \qquad (5)$$

Where:

- η is the propeller efficiency;
- a is the axial interference factor, equal to $w/V\infty$.

This efficiency is around 0.75; therefore it is possible to determine the mechanical power required by the internal combustion engine (Eq. 6).

$$Pmci1 = P/0.75 \qquad (6)$$

To size the two thrusters, the vehicle rotational speed around the vertical axis is required as a design parameter. It was assumed to impose a 90 degrees rotation in 3 seconds. To size the thrusters, a fundamental quantity to be imposed is the distance between the thruster axes and the airship center of gravity. To calculate the force required for the rotational features above exposed, the following formula was employed (Eq.7).

$$Fm = 2\,(J\, \dot{w}) \,/ (w\, d) \qquad (7)$$

Where:

- Fm is the force required by the thrusters, expressed in N;
- J is the moment of inertia of the airship set to be equal to a single ellipsoid, expressed in kg/m^2;
- $\dot{w}$ is the angular acceleration expressed in rad/s^2. The acceleration value has been valued considering a triangle distribution and then assuming that the speed reaches the maximum value at time t '= $t/2$. The angular acceleration value is therefore estimated using the average velocity over time t ' equal to $\pi/12$ rad/s;
- d is the distance from the center of gravity, assumed equal to 5 meters;
- 2 is a safety factor.

At low rotational speeds the performance of the propellers decreases significantly; it can be considered a reference value of 0.3 for the efficiency. Using this data it is possible

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to determine the power that must be supplied by the electric motors for moving the propellers (Eq. 8) and the diameter of the latter (Eq. 9).

$$Pm = (Fm\ w\ d)/(1000\ \eta_m) \tag{8}$$

Where:
- Pm is the power that must be supplied by the electric engine, expressed in kW;
- η_m is the propeller of maneuver performance;
- 1000 is a conversion factor.

$$D = \sqrt{\frac{2\ P\ \eta_m{}^3\ 1000}{\pi\ \rho\ (\ w\ d\ )^3\ (1-\eta\ )}} \tag{9}$$

To go back to the power required to the internal combustion engine according to the power supply line used for the handling phases, the efficiencies of the electric motors and alternator need to be considered. For the brushless motors, the efficiency is very high and can be estimated as 0.9; also the generator efficiency can be assumed 0.90.Therefore the power that must be supplied by the internal combustion engine for maneuvers is calculated by the (Eq. 10).

$$Pmci2 = Pm\ /\ (\eta mbr\ \eta alt) \tag{10}$$

Where:
- ηmbr is the brushless motors efficiency;
- ηalt is the alternator efficiency.

V. Stations

It has been hypothesized to load the gas into the airship withdrawing it from a tank in which the gas is stored at a pressure of 30 bar. To determine the pressure that the gas must achieve in order to be placed in gas bags it must use the state equation of van der Waals. The objective is to determine a pressure such that the natural gas to the cruising altitude presents the same density as air, in order to provide zero upwards thrust. The application of van der Waals equation conducted on natural gas has led to consider a pressure of about 1.67 bar. To realize the pressure drop wanted, reference is made to a Natural gas Pressure reduction group of first stage. The regulation generally takes place by means of two lines of equal potential, one in operation and one as reserve and each consisting of two regulators, one in operation and one emergency, so that if one were to present an interruption for technical reasons, the other would begin to function. On each reduction line, there are a filter for purifying the gas from any impurities, a heat exchanger to cope with the lowering of temperature caused by the pressure drop which would cause problems to the system. These components are placed upstream of the pressure reducing system, which is realized using a Joule Thomson valve.

The output pressure and temperature at which the gas will be introduced into the bags are imposed using an attacking system similar to that used in the automation field to the cylinder trucks.

Regarding the discharge phase, it is assumed to download the gas into a tank and then enter into the low pressure network. Therefore it has considered 0.04 bar as reference pressure. In order to accomplish this, the use of a 2° stage industrial reduction is considered. Also in this case, the plant design solution provides two expansion lines: one for function and the other one for emergency. Upstream of the reduction system a filter is placed. It is also necessary to provide a line and an emergency regulator with safety and relief valve. The construction features of reduction and measurement cabins comply with the specifications of the D.M. 24/11/1984 "Fire Safety for the transport, distribution, storage and use of natural gas with a density no greater than 0.8".

VI. Mission Profile

In this section, the flight issues are presented. The route connecting the University Campus of Savona with the industrial area of Bene Vagienna, located in the province of Cuneo, has been considered as the mission. Ideally the mean will fly over the motorway A6 between the exits Savona and Fossano.

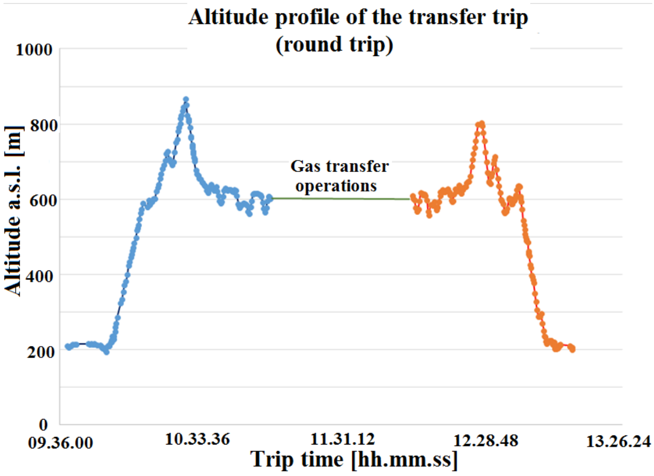

Fig. 7. Altitude profile of the trip.

This is justified by the fact that theoretically the path is the one that has the lowest average altitude. To cover this distance, estimated in 80 km, a timeframe of about three hours has been considered, because airship cruising speed has been set around 40 km/h, but time of uploading and downloading of the airship has to be considered. To evaluate the cruising altitude, the elevation profile has been analyzed with the help of OpenGTS software. Then the obtained values have been increased to 150 meters to obtain the maximum altitude at which the airship should travel in safety conditions.

Fig. 7. shows that the maximum height is near 900 meters above sea level. Obviously, to avoid having to adjust the buoyancy in flight, the cruising altitude has been set to 900 meters.

For the regulation of the mission it has been relied on the ENAC normative for remote controlled vehicles [7]. The airship is identified with the acronym SAPR because it is an Aircraft Remote Piloting System utilized in specialized, scientific, experimental and research operations. In particular it is a SAPR with an operative takeoff mass between 25 kg and 150 kg. This implies that operations are considered to be of critical nature. It is also adopted anremote controlled type BVLOS (Beyond Visual Line Of Sight), as the operations are conducted at a distance that does not allow the remote pilot to remain in direct and constant eye contact with the airship. In the delineation of the mission the organization of neighboring airspaces and airports has been considered. Indeed, each airport has limited or prohibited traffic areas to ensure safety; a distinction can be made between CTR (Control Area) and ATZ (Aerodrome Traffic Zone). The first acronym indicates a controlled air space that extends from the soil surface up to a specific upper limit. Its lateral limits contain the portions of routes of take-off and landing near the airport. In these areas drones flight is allowed up to a maximum height of 70 meters. The second acronym identifies an airspace of defined size established around an airport for the protection of take-off and landing operations; there drones flying is forbidden (Fig. 8).

Fig. 8. Map on trafficking carried out by the drone. Brown represents the ATZ and blue the CTR.

VII. Emergency Management

In the mission evaluation some measures of fundamental importance have been taken in order to deal safely with the most relevant emergency scenarios. Three of them have been considered: piercing of the bags containing the lift gas, reliability of the powertrain and risks related to flammability of natural gas.

Regarding the possibility that problems to gas bags containing helium might occur during the flight, two solutions have been considered to mitigate the risk. As it has already been said, it has been decided to oversize the number of helium bags; this allows to have some spare useful bags to compensate any dispersion of part of the flotation gas. Moreover it has been also decided to equip each bag with pressure switches able to provide the control centre, in real time, information about the state of the gas bags. In this way, if some problems occur to the gas bags, it would be possible to promptly intervene to safely land the mean and provide for the maintenance operations. Usually in aeronautical sector means and control systems are equipped with redundant components for each of the most important operations that must always be guaranteed for the conduction of operations in complete safety. In this aspect, the powertrain adopted in this project presents a weak point; Indeed, the propulsion propeller and the thrusters are guaranteed by the operation of the internal combustion engine. This choice is dictated by design, economic and environmental reasons, and for a prototype, this problem is not particularly relevant. The possible use of a second internal combustion engine in fact would require higher size and a different amount of lift gas caused by the increase of overall weight. To reduce the risk of malfunction of the internal combustion engine, it is possible to adopt one characterized by high quality standards. Then it can refer to a special motor characterized by:

- Ability to work in continuous service;
- High-quality mechanical materials;
- Overheating resistance;
- High performance.

The natural gas presence rises the problem of a potentially explosive mixture with oxygen; therefore safety measures must be adopted to prevent from the formation of a source of ignition. For the analysis of this issue it was considered a maximum air temperature in the interior volume of the airship around 50° C. A potential ignition may be caused by a possible friction between the cage and the valves that could give rise to sparks. To eliminate these risks it is opted for the application of the cage above the polyurethane casing. In this way, the ignition energy can be generated only from problems related to electrical equipment. To reduce also these risks it was decided to realize electrical systems with technology suitable for explosive atmospheres and to employ elastomeric materials able to function under the effect of fire.

After dealing with prevention systems to be adopted in the airship, some safety systems have been studied, in the event that a fire should be triggered. Obviously the propagation of a fire inside the airship would have destructive effects, so it is necessary to use materials able to prevent the spread of fire. All the materials used must therefore be manufactured to meet the flammability requirements of UL 94 5V test.

VIII. Conclusion

This research study has shown that the transport of natural gas via airship is potentially achievable. The airships are currently able to give (and probably will be even more in the future) effective responses to many needs in many areas. Currently, several countries are active in the industry with companies that produce or operate airships. Some specific features of the airship make it particularly interesting:

- Great autonomy and durability in flight: the lift force is not generated by aerodynamics but by buoyancy, thus saving fuel;

- High load: increasing the amount of lift gas can greatly increase the transport capacity. In addition, the large internal space provides low size loads or forms incompatible with most of the other means of transport;

- Energy efficiency: in the airship, being the lift assured by gas, engines are used only to move, this results in energy consumption per hour of flying extremely low. Also it can cover the surface of the airship with a large solar panel which allows to minimize the use of non-renewable resources.

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- Low environmental impact (emissions, noise, turbulence): low power consumption has the immediate reflection of a lower environmental impact. In fact, the levels of air and noise pollution are almost negligible with respect to a traditional aircraft.

- Ability to carry out operations in areas without airports: airship can land and take off vertically, therefore it doesn't need long runways. This does not mean that it can operate without an underlying infrastructure, which are instead necessary.

- Safety: security is guaranteed by the possibility to remain in flight even in case of all engines shutdown, the possibility to land (and to make emergency supplies) even in the absence of airports, the low speed to the moment of landing and the take-off, the poor sensitivity to certain atmospheric phenomena such as fog.

Also innovations in aviation have allowed an improvement of the airship features:

- Progress in meteorology, both understanding of atmospheric phenomena such as real-time availability of data on the entire planet's climate, allow higher levels of safety;

- Technological advances: the introduction of GPS overcomes one of the major difficulties of navigating of historical airships, which is determining the vehicle position in the absence of reference points;

- Improvement of structural materials: new aluminum alloys, titanium, carbon fiber, Kevlar, composite materials;

- Improvement of materials for the casing: replacement of tissues and natural membranes with synthetic materials such as nylon, polyester, polyurethane.

These allow considerable savings in the weight of a component that constitutes considerable part of the mass of an airship, longer life, lower permeability to gases and lower maintenance requirements.

- Reliability, efficiency and high power to mass ratio of the "hot plug" internal combustion engine.

- Process automation;

- Remote Steering: possibility of cost and weight reduction for numerous tasks and missions to face with risk levels otherwise unacceptable.

Based on these considerations, it is believed that a greater knowledge of the airships would be required, since it is an unexplored territory or under-exploited with considerable potential for improvement and growth. Moreover a study of the issues shows how unfounded are the historical legacies that lead to associate the airship to poor security. For a return of the airship to its former glory we should make targeted investments aimed initially at improving knowledge on the matter and to form specialized and then produce adequate technical infrastructure required to refine the construction and operational techniques.

Future developments will face the task to build a down-scaled model to obtain experimental data to be compared with the theoretical ones found in this study; moreover, deeper logistics [8] and simulation [9-11] studies will be carried on.

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