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Lighter Than Air Activities at ONERA : A Comprehensive Overview

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Abstract
ONERA has been working on Lighter than Air (LTA) subjects for the last 10 years.
Activities on overall design and flight modelling of LTA systems have been achieved, including control laws to address cruise phases as well as more specific flight cases as hover or station keeping. Aerodynamic models have been developed combining both experimental and numerical approaches.
Some additional activities have been led: structures, environmental conditions (Lightning, Icing and Aerology). The goals are both to investigate on specific issues linked with LTA applications and to integrate them in the design process. The purpose of this article is to provide a comprehensive review of the main results achieved by ONERA.

1. Introduction

Lighter than Air (LTA) technologies are experiencing an important revival, which can be seen by the number of LTA programs currently in development worldwide.
LTA systems have moderate power consumption compared to aircraft vehicles, which can be a clear advantage in nowadays environment challenges. This also makes LTA a great platform to host more or full electric propulsive concepts. Another asset of LTA systems is their ability to low speed, eventually hover. Thus LTA can provide long endurance or persistent solutions. It is also well known that LTA suffer from two main disadvantages, buoyancy leads to large dimension vehicles, moreover LTA systems are very sensitive to environmental conditions especially wind. There are also many technical specificities to deal with, which offer a large field of investigation for research.
Two main applications are envisioned which are heavy lift transportation, and observation/ surveillance. Both applications are dual. Great perspectives are anticipated with the integration of recent technological breakthroughs, in terms of materials, electric propulsion technology and control laws.
In this context, ONERA has been involved in several programs for the last 10 years : on the one hand several programs supported by BPIFrance/SAFE Cluster, Horus which aims at developing a medium sized tethered balloon, Neptune, an airship with sea-landing capacity, and Aerolifter a balloon-logging solution on long distances; on the other hand ONERA led two programs for DGA: CERBERE, experimentation with a tethered balloon and MESSAGER design for surveillance airship. Currently ONERA is in Stratobus™ and Flying Whales programs.
The purpose of this article is to provide a comprehensive review of the main results achieved so far by ONERA

2. Overall Design

ONERA has acquired a significant expertise in LTA overall design and all its associated technical aspects. References [1][2] shall bring an initial overview on LTA systems design. The first step of the process is to determine mission and operational requirements. At this point a functional analysis approach can help to refine and build up specifications. The overall design loop for an airship is described in Figure 1.

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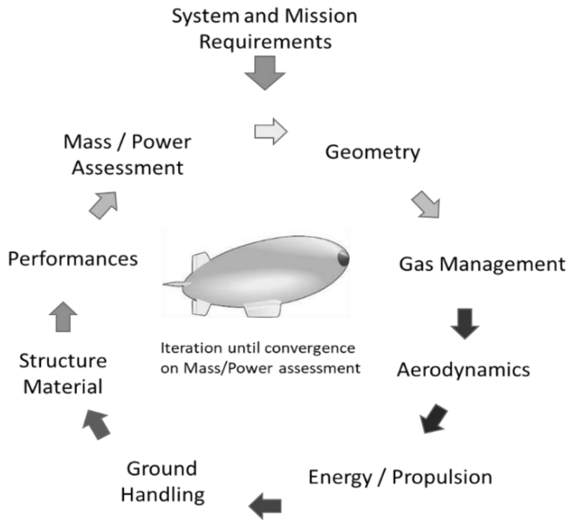

Figure 1: Overall Design Loop

The functional analysis and mission requirements allow to set the key performance parameters, such as Speed, Altitude, Payload or disposable mass, Flight duration. At this point, some design deterministic choices: manned/unmanned, airship structural type, conventional/hybrid, energy supply, gas management strategy, etc. have to be done because they have direct consequences on the assumptions for the proper execution of the design loop.

An initial geometry is set, mainly from experience or state of art considerations. Then an iteration is performed on each disciplinary modules. Some modules can be tightly coupled so there can be inner loops or trade-offs to be made. The design loop ends with performances and mass/power assessment and direct comparison from system and mission requirements. Then an iteration on geometry until mass/power assessment meet requirements.

Some disciplinary modules are rather close to traditional aerospace engineering, yet showing some specificities that shall be dealt: aerodynamics as shown later in this paper, energy/propulsion, material or structure.

Some other modules are specific to Lighter Than Air vehicles. At first there is gas management, i.e. the analysis of the variations from buoyancy and weight. This fairly depends on the use case and the nature of operations. Difference between altitude min altitude max, atmospheric/environmental conditions, superheat, load exchange, fuel compensation, lifting gas leaks shall be among the considerations to be able to delimit impacts on static heaviness and determine the level of fidelity to be achieved for the model. The second is ground handling, which shall not be forgotten has this is where the major part of incidents/accidents have happened during ground proximity operations and where the structural constraints on vehicle can be severe [3]. The latest is obviously non rigid materials.

On LTA systems an increase in total mass requirements has great consequences on overall design, starting with significant increase of sizes, as well as mechanical constraints This have major impacts in the design on disciplinary levels.

At preliminary design level, the key point is to identify the uncertainties and to allocate them in design margins. The most important is the structural factor (Is) initial setting and all the mass contributors linked to mechanical constraints: ground handling, pylons, fins, gondola, payload, load exchange, etc. If not taken account properly this shall increase the Is and this would lead to major evolutions of sizes.

As an illustration, medium altitude long endurance conventional airship for observation mission. Major characteristics are summarized in table 1.

Table 1: Requirements for medium altitude long endurance airship

Max. Altitude	7000m MSL
Atmosphere	ISA Std
Aerostatic Margin	10%
Speed (Cruise, station)	120km/h - 50km/h
Disposable Load (incl. Payload)	7000kg
Propeller Efficiency	0.8

By applying both static equilibrium and power formula, volume and installed power are calculated as a function of structural factor Is and drag coefficient Cx. Is is set between 0.25 and 0.33, Zeppelin Hindenburg has an Is of 0.35.

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Drag coefficient is set between 0.025 and 0.045. Cx 0.04 is used as a standard value for preliminary design even if CFD assessment results show far lower values. The addition of appendages, guylines and any offset devices lead to a penalty on drag as investigated in [4].

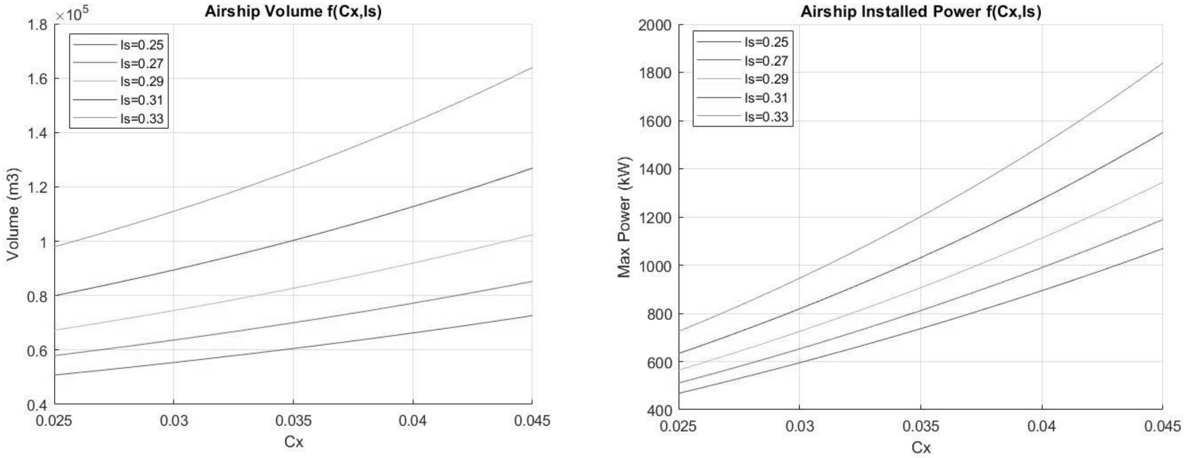

Figure 2: Volume and Installed power

The effect of Is is crucial. For a Cx 0.04, a change for the value of Is from 0.29 to 0.31 led to a change of volume from 92000m3 to 112800m3. If a reduced value of Cx = 0.03is considered, for Is=0.29 this led to a volume of 74600m3. Cx is also linked to target speed and installed power. An incorrect drag coefficient assumption will lead to a reduction of achievable maximum speed at fixed power.

Buoyancy/mass and Speed/power are tightly coupled through Is and Cx. An optimistic initial statement for Is or Cx will lead to either a lower level of requirements or a large increase of volume/installed power to meet requirements.

Other considerations that change the design process in a first order is the range of altitude and deterministic choices : building architecture (rigid, non-rigid or semi-rigid) and energy/propulsive architecture (thermal, more/full electric, solar,…). The two latest change the settings in terms of specific mass.

The design process is used to elaborate airship concepts as presented in Figure 3. It meets the requirements on table 2 and all design modules are at preliminary design review level. Deterministic design choices are semi-rigid architecture, unmanned or manned operations and thermal propulsion with combined gas turbines/ piston engines and vectorized thrust.

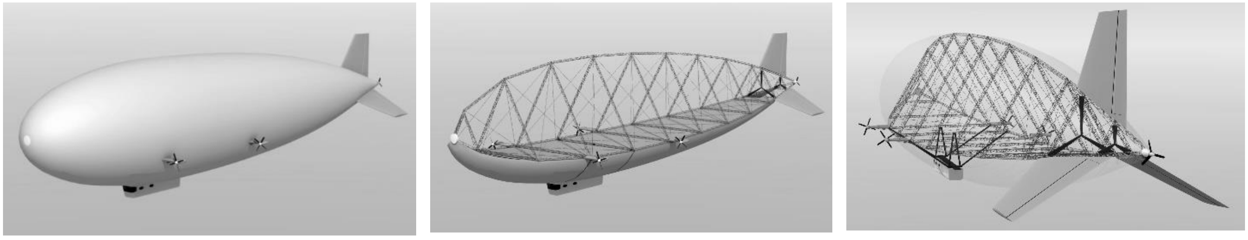

Figure 3: Visuals from a concept of medium altitude long endurance surveillance airship

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3. Flight Modeling

3.1. Flight Simulation Tool

ONERA is involved in several aerostat programs and one of its main activities is to elaborate flight models. Consequently, the need to have a flight simulation tool dedicated to aerostats naturally emerged, to support these activities and to capitalize all the developments. The structure of the simulation tool (Figure 4) is straightforward, because the aim is to define the forces and moments applied to vehicle and to apply Newton's Laws of motion. However there are some specificities that will be developed later in this paper.

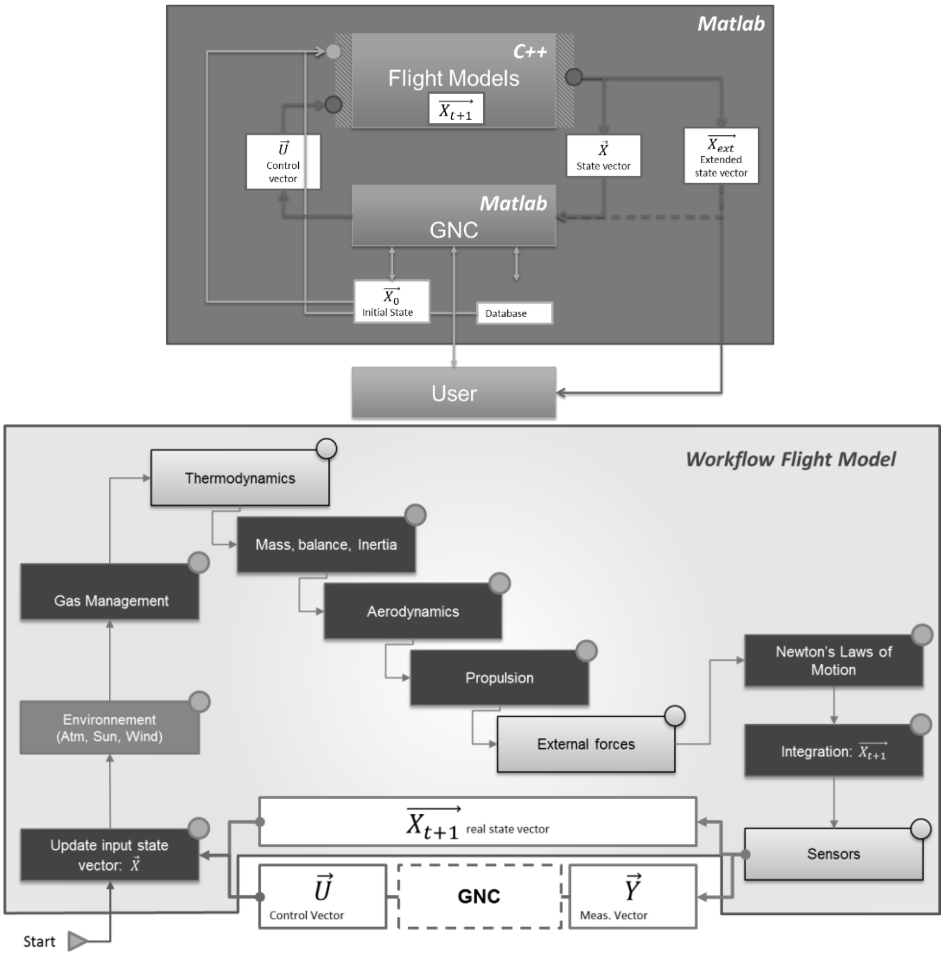

Figure 4: ONERA Flight simulation tool

3.2. Equations of Motion

Equations of motion for an airship are described in [5][6][7][8][9]. The main difficulty comes from the added mass terms that are put in left member of equations and that are aerodynamic terms. Depending from the way of obtaining these terms (CFD, Experimental,…) and the definition in the aerodynamic model, some terms shall be assessed and eventually removed. ONERA developed its own set of equations of motion by focusing on this point. Aerodynamic model is mainly issued from experimental data. The equations of motion have been made compliant with wind dynamic local evolution (gusts).

3.3. Cable Modeling

The need of cable modeling is issued from tether balloons. Traditional approaches from [10][11] were implemented. There are some additional development for balloon logging applications on long distances (2km) where it is required to have a computation cost effective algorithm. Furthermore a simplified model inspired from helicopter applications and slung load operation [12] was also implemented to deal with load exchange problems. All these additional abilities are encapsulated into modules that can be plugged in the flight simulation tool.

Figure 5 shows a typical tethered balloon flight behavior with a test case with wind direction change. Cable is discretized in 100 elements. Rotating base dynamic behavior is also modeled.

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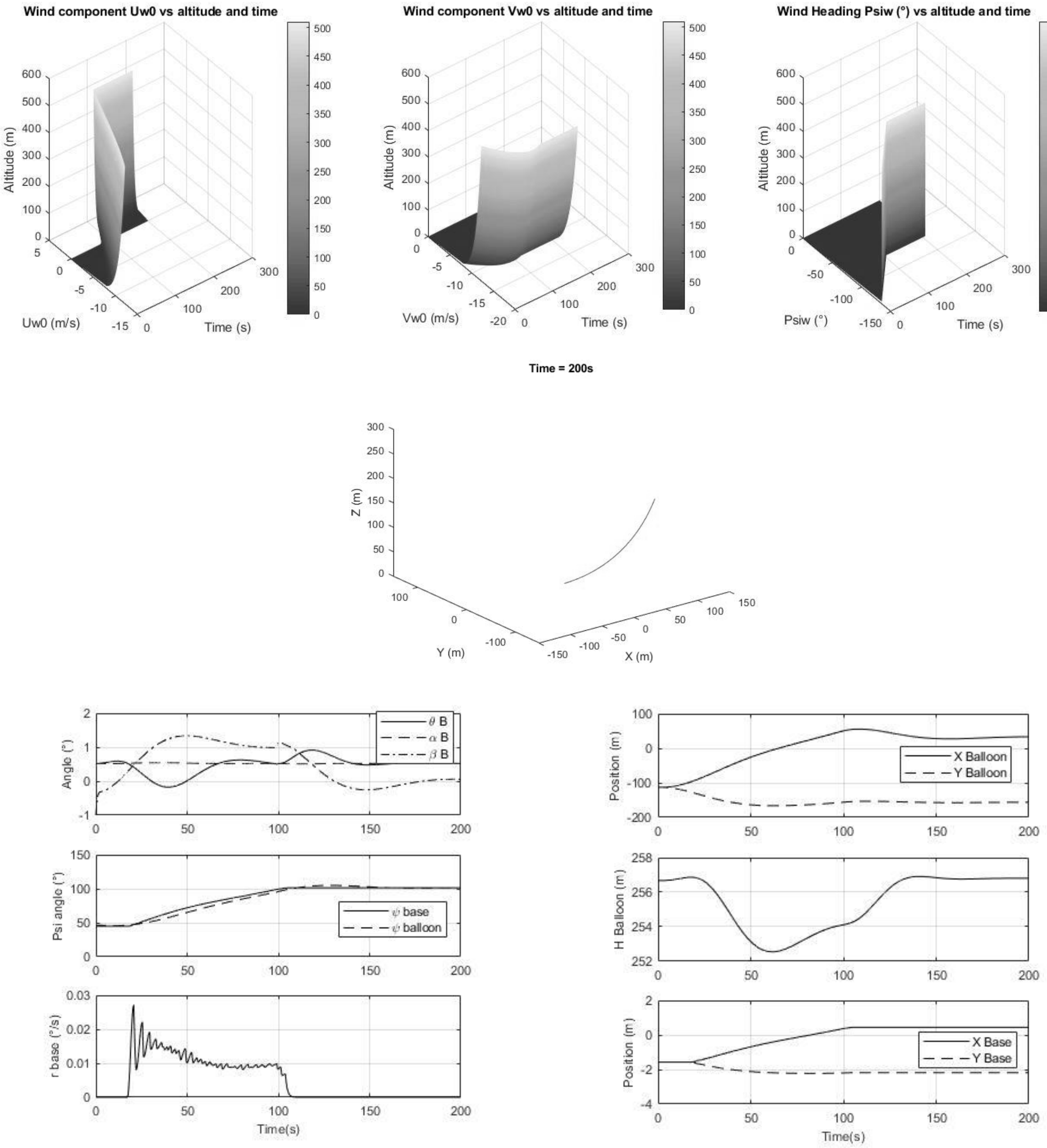

Figure 5: Tethered balloon trajectory characteristics in a wind heading change

Figure 6 shows results for slung load trajectory and coupling with airship, for a test case with a log pitch oscillation (10° initial pitch angle).

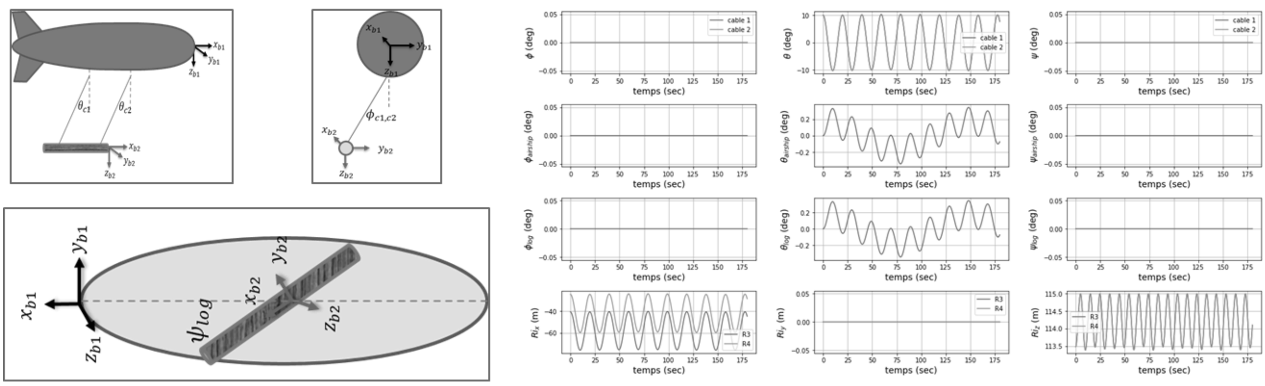

Figure 6: Slung load model - 10° initial pitch angle perturbation case

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3.4. Thermal Modeling

This activity is linked with gas management design and is coupled with thermodynamics. Thermal modeling is of primary importance for stratospheric LTA applications: on climb and descent performances where air shall be get in or out the envelope in large amounts and during station keeping where there are thermal management issues even increased when solar panels are mounted on top.
Figure 7 shows the thermal environment introduced into the model.

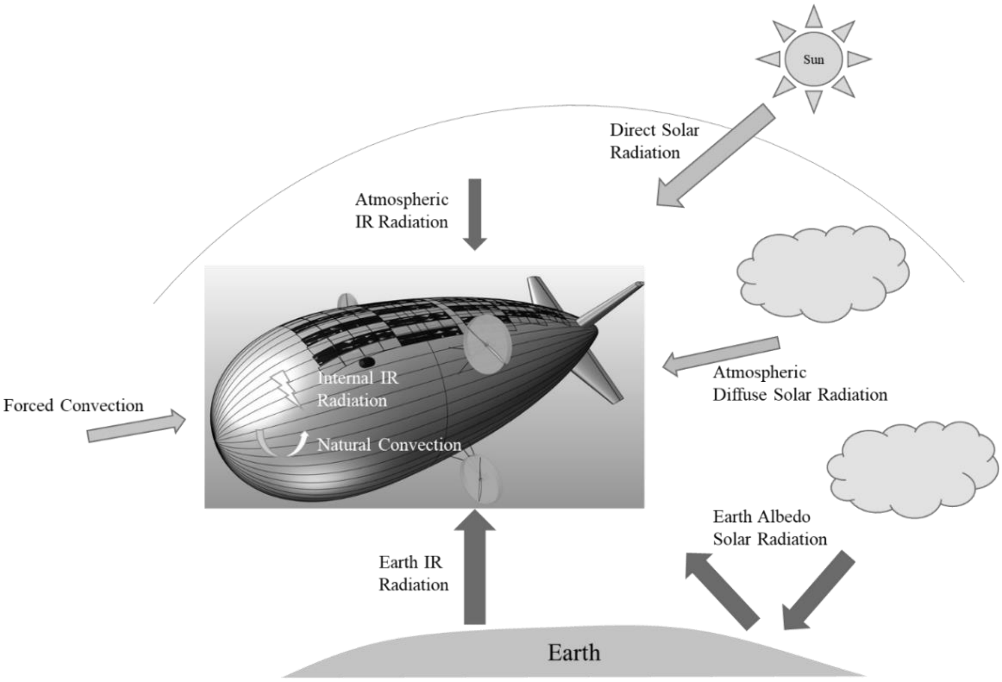

Figure 7: Thermal environment for an airship

As described in [14], radiative and convective terms can contribute in similar order of magnitude and can vary a lot depending on flight conditions. Besides response time of thermal phenomena is fairly larger than the one of LTA vehicle: this introduces complications for overall performance assessment.

For tropospheric LTA applications if the concept of operations exhibits some situations where long duration of superheating (for instance load exchange while hovering), thermal assessment shall be assessed thoroughly. Eventually thermal management solutions shall be designed. Unfortunately this shall have a mass penalty.

3.5. Performance analysis

Some results obtained with the simulation tool, flight model with GNC loop. Figure 8 shows station keeping trajectory for a high altitude airship. In blue a strategy of low speed racetrack and in red a strategy of tacking facing wind.

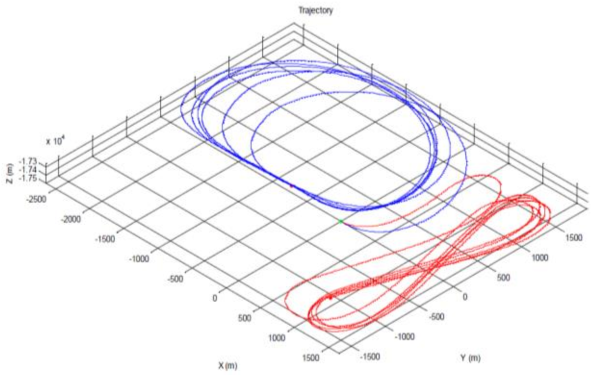

Figure 8: Station keeping trajectory for a stratospheric airship

Figure 10 shows the effect of a lateral gust during as level flight at cruise speed in trimmed conditions (open loop). The airship experienced a lateral drift as well as a downward motion with the initiation of roll/yaw pendulum modes.

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The airship gets back to initial trimmed conditions showing the stability of the system. The shape of gust is representative to airworthiness requirements (1+cos shape, 7.6m/s gust at 100km/h velocity, with a length equal to length of airship as shown in Figure 9).

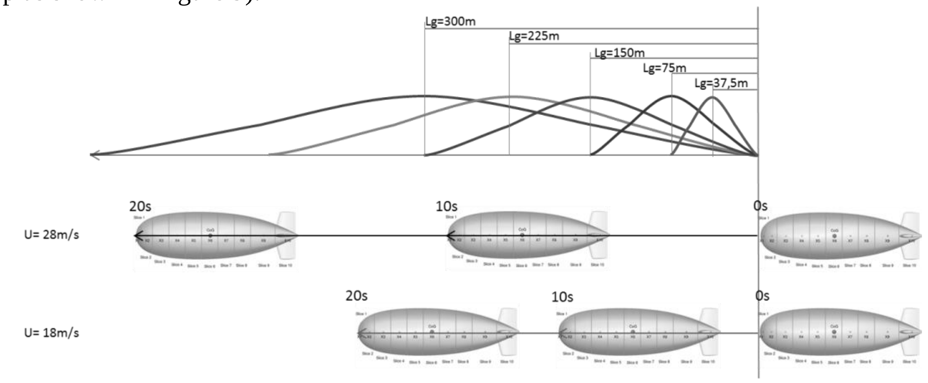

Figure 9: representation of gust relative to regulation- application to a 150m long airship

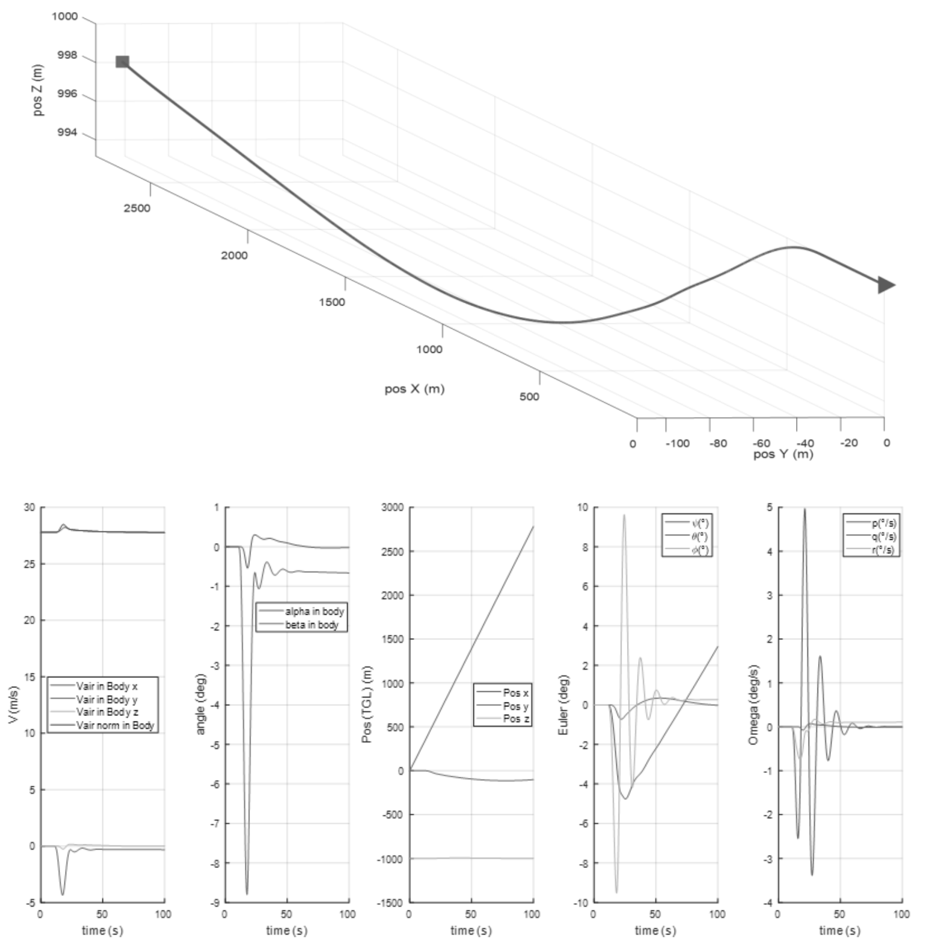

Figure 10: Effect of a lateral (1+cos) shape gust on a trimmed level flight (large transport airship).

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4. Aerodynamics

4.1. Generalities

Aerodynamics activities at ONERA are led by DAAA department (Aérodynamique, Aéroélasticité et Aéroacoustique). Concerning airship aerodynamics, there are some specificities. At first there is a need to define an aerodynamic model within a broad range of aerodynamic angles (angle of attack, sideslip angle), this is especially true when there are low speed/ hover requirements in the concept of operations. Above 15°, some nonlinear phenomena can happen. Moreover damping dynamic terms (effects of angular rates relative to the flow) have an essential role in airship stability thus these terms shall be assessed properly. Last but not the least, airship added mass terms can't be neglected. Their assessment can become difficult for non-classical geometric shapes as the state of art is scarce. Last but not the least, airships are very sensitive to gust.
All the results feed aerodynamic models that are integrated into flight simulation tool.

4.2. Experimental Approach

As the airship may encounter a large range of situations in terms of position of air-velocity relative to body frame (pure longitudinal flow as well as pure transverse flow), wind tunnel tests aim generally to explore a very wide range of angle of attack and sideslip. Moreover effects of angular rates (in fact mainly pitching or yawing rate) have to be identified. Such tests are generally carried out in the L1 wind tunnel, situated in ONERA-Lille. Main specificities are detailed hereafter. ONERA-Lille operates also a vertical low speed wind tunnel (ONERA-SV4) which is characterized by a open large test section (4m diameter). This installation wind tunnel has been recently used to evaluate effects on a model partly or fully immerged in the flow, in order to validate models of gust effects.

L1 wind tunnel

The ONERA-L1 wind tunnel is a low speed, Eiffel type wind tunnel with a streamline return corridor (Figure 11). Three types of test sections are available. For airship hull characterization, the open test section is selected. This open test section has a 2.4 m diameter and a length of 2.4 m. Test mockup length is generally about 1m. In open test section configuration a speed of 60 m/s can be reached.

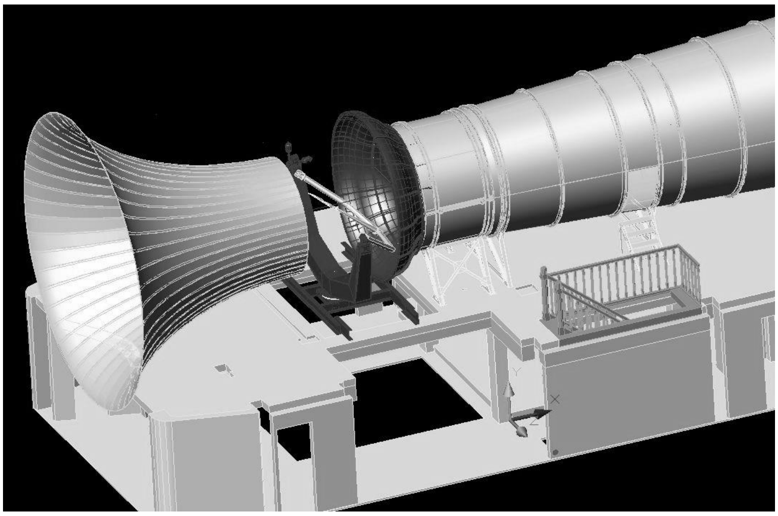

Figure 11: L1 wind tunnel configuration « open test section » and « PQR » rig

PQR rig

For airship hull characterization, the PQR apparatus is generally used (Figure 12). It is a rotation rig with three degrees of freedom about the main body axes (Euler angles ψ, θ, φ). The θ axis is actuated with an electric servo motor. This allows alpha-sweeps and pitch oscillations when the model is installed in the upright position (phi=0) and beta-sweeps and yaw oscillations when it is rolled of phi=90°. The main kinematics characteristics of the apparatus are described in the table below.

Angle	Description	Range (°)	Angular velocity (°/s)
θ	Angle of attack	-110 à 110	400 (max acceleration 9000°/s²)
ϕ	Roll angle	-180 to 180 with step of 5	0 (currently, motorization is planned)
ψ	Heading angle	-20 à 25	5

Table 2: Definition and measure range of rig angles of « PQR »

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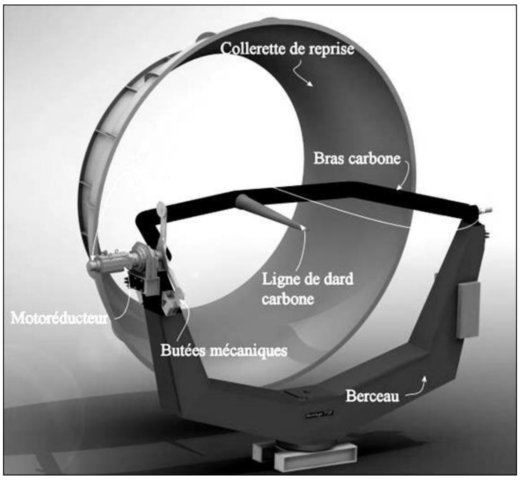

Figure 12: CAD of PQR rig

The L1 windtunnel facility equipped with PQR rig enables the measurement of a large range of aerodynamic angles as well in forced oscillation mode, of dynamic damping coefficients. Consequently, this facility is well adapted to airship aerodynamics characterization.

Six windtunnel test campaigns have been achieved for the past 7 years in the frame of several aerostat programs: Tethered aerostat Horus, Stratobus^{TM} (Figure 13) and FLYING WHALES LCA60T. Typical duration of a test campaign is 4 weeks. The model is mounted on a rear sting, internal dynamometer allows to measure external forces, and the model can be also equipped with skin pressure taps in order to get local aerodynamic data.

The classical domain covered by such tests is very wide as situation of pure longitudinal flight in calm atmosphere has to considered as well as pure transverse flow (case of lateral or vertical gust impacting on the whole length). Aerodynamic coefficients are measured therefore in [-90°, 90°] angle of attack and sideslip range (Figure 14).

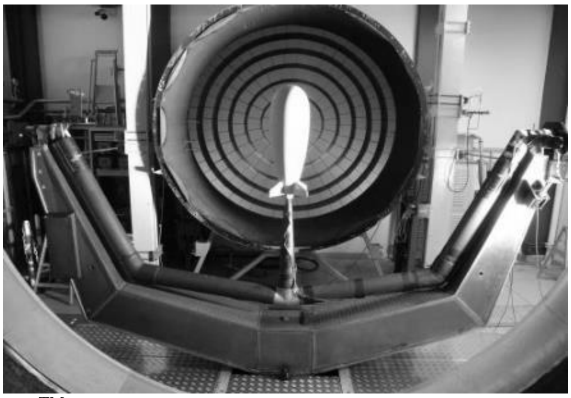

Figure 13: Stratobus^{TM} mockup tested in L1 windtunnel facility (Mockup is 1m length)

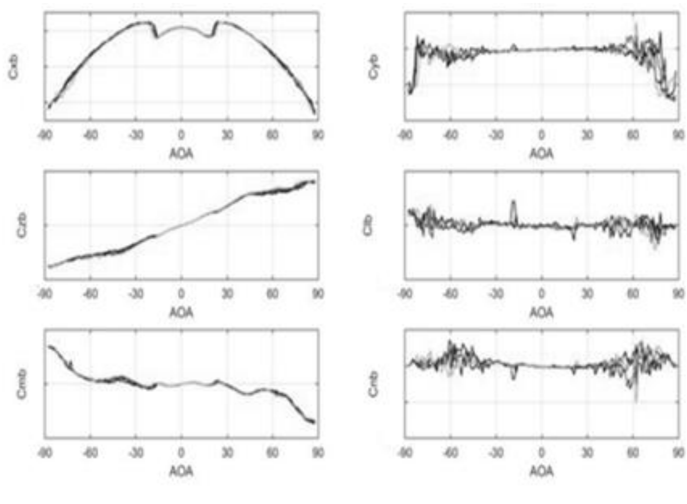

Figure 14: Sample of aerodynamic coefficients (body frame) obtained from windtunnel tests

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4.3. Numerical Approach

CFD approach is also generally also done. These calculations may be useful for the preparation of the wind tunnel tests: definition of the most appropriate transition tripping and location on the model for example, and also for the extrapolation of the experimental data from low to high Reynolds number regime or assessment of mounting interaction. Static conditions but also dynamic motion (rotation of the body in the flow) are considered by CFD. With ONERA flow solver elsA.

4.4. Aerodynamic Modeling

Results from both experimental and numerical approaches provide the core of the aerodynamic model. Additional corrections are provided from comparison with database. The accuracy of the model can be increased by identification study by comparison with flight tests measurements and appropriate post processing analysis.

4.5. Gust model

One of the most sensitive and crucial issues for the lighter-than-air vehicles is the dynamic behavior in turbulent atmosphere and in gusts, including when flying at low altitude.
The work carried out aims at developing models, at validating numerical simulations used during the design stage and at improving the flight simulators.
This is done by coupling various approaches: analytical developments, CFD in stationary and non-stationary conditions, wind tunnel tests and flight tests on scaled models.

Due to the high length of the airship gust effects may impact only part of the vehicle. Analytical approaches are dedicated to the representation of the effects due to the local variation of air-velocity along the hull when the airship is traversing a gust. A classical way for the modelling is the “slice” method, and the use of the theoretical repartition of normal force along a slender body in inviscid conditions [16].
Improvement of the modelling may be obtained through experimental tests in wind tunnel and/or CFD computations, a major improvement is relative to real fluid effects (detached flow at the rear part of the hull when high induced angles due to the gust, etc.). In the field of the PhD thesis conducted at ONERA and with the support of Flying Whales Company, these two ways (CFD and wind tunnel tests) have been explored on a 1/3.5 ellipsoid [14]. Wind tunnel tests with model partly of completely immerged in the flows allows to identify effects when the vehicle is in pure uniform flow or in a local transverse flow.

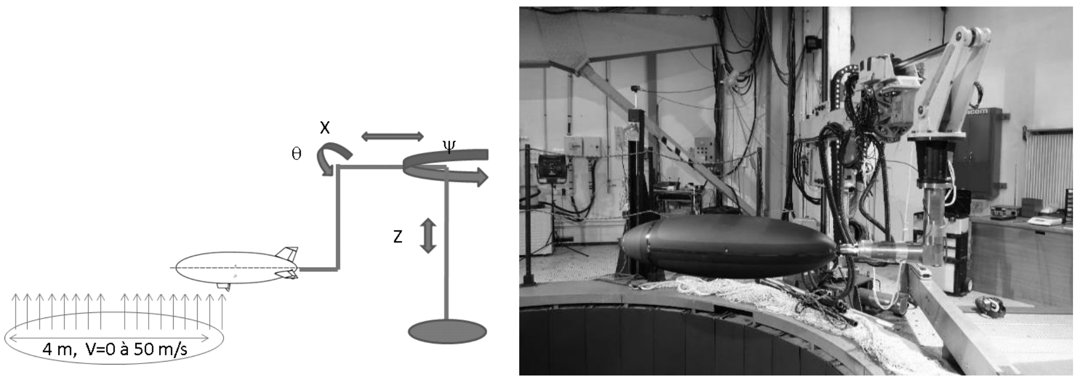

Figure 15: Tests on ellipsoid in the vertical wind tunnel SV4 at ONERA-Lille – effects of transverse flow

Development of models allows for example to get effects in terms of induced normal force and moment when the airship is traversing a gust. The case of the classical (1+cos) vertical gust with a width equal to the length of the vehicle is illustrated (Figure 16).

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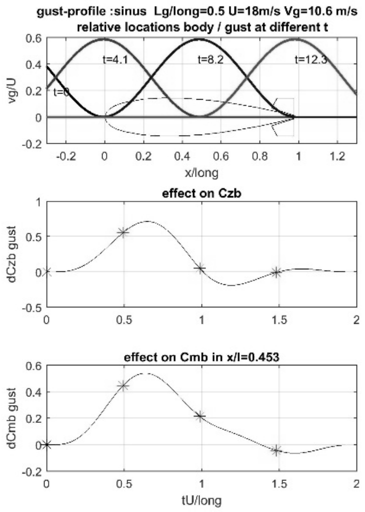

Figure 16: Simulation of flight through a (1+cos) vertical gust – induced normal force and pitching moment

A complementary approach is to perform free flight tests on reduced scale models. This consists of flying a free flight scaled model through lateral gusts whose characteristics are calibrated. The behavior of the vehicle is measured during this flight (trajectory, angles…).

This approach was applied to a 5m long remote-controlled airship model, flown in the free flight laboratory at ONERA-Lille (Figure 17, Figure 18); a video is proposed in [17]. Thanks to its large dimensions (90x20x20 m3) this laboratory originally built for tests on catapulted aircraft models, is ideal for this kind of experiments. An open circuit wind tunnel located in the center of the laboratory allows a lateral wind to be generated locally: an area of perturbed atmosphere, perfectly known and with a velocity profile adjustable in shape and intensity, is simulated. This setup is completed by a video-trajectography system. The flight trajectory is then compared to the simulation in order to validate or correct the aerodynamics modelling.

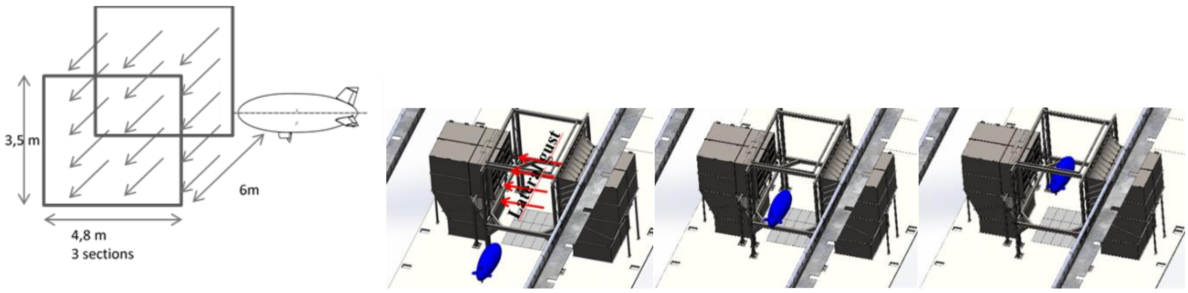

Figure 17: Schema of the lateral wind generator and flight of a 5m model

Figure 18: free flight laboratory B20 at ONERA and flight of a 5m model through the lateral wind generator.

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5. Structures

Concerning non rigid materials, ONERA has led for many years tests research activities on weathering issues mainly for stratospheric balloons. For overall design purpose, references [18] and state-of-art are used to set up a preliminary choice of multi-layer material and evaluate its weight.

For rigid structures, the activity is broken down as following: a mesh of structure (Finite Element Model) issued from geometry is realized. The allocation of efforts (pressurization, buoyancy, weight, aerodynamics, ground handling,…) is then performed on the nodes of the FEM mesh, followed by a computation, so that to assess the efforts on each FEM elements (frames, purlins, rods, cables,) and the safety margins in terms of ultimate strength and buckling. Then the suitable elements are determined from a catalogue. At the end of the process the overall structural mass is assessed and compared to objectives at overall design level. If it is non-compliant, another computation shall be necessary, until convergence.

ONERA led structural assessment linked to overall design loop for both semi-rigid (Figure 19) and rigid airship concepts.

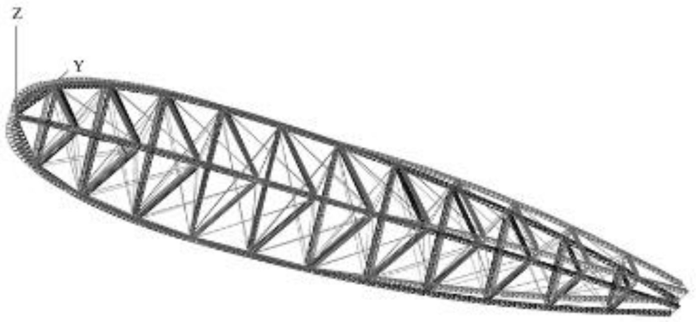

Figure 19: Finite Element Model design for a primary structure (semi-rigid airship concept)

6. Environmental Conditions Studies

6.1. Generalities

ONERA has a strong expertise in environmental conditions in aeronautical domain, mainly applied to aerodynes (fixed-wing or rotorcraft). The purposes of the activities described hereafter are both to investigate on specific issues linked with LTA applications, increasing the spectrum of ONERA expertise and at overall design level to integrate the potential constraints issued form these investigations as soon as possible in the design process.

6.2. Lightning Direct and Indirect Effects (LDE/LIE), Electrostatic Discharges (ESD)

The process used for Lightning Direct Effects is similar to those performed on aircraft and can be described as following: initial inputs are system definition concept of operations and strategy vs. lightning strike. The process starts with the definition of system electrical topology, followed by a phenomenological study. Then a zoning can be defined. From this point lightning damage assessment can be performed, mainly by tests. ONERA has used GRIFON test facility (Figure 20). The results from LDE risk analysis contribute the overall design assessment and tradeoff decision making.

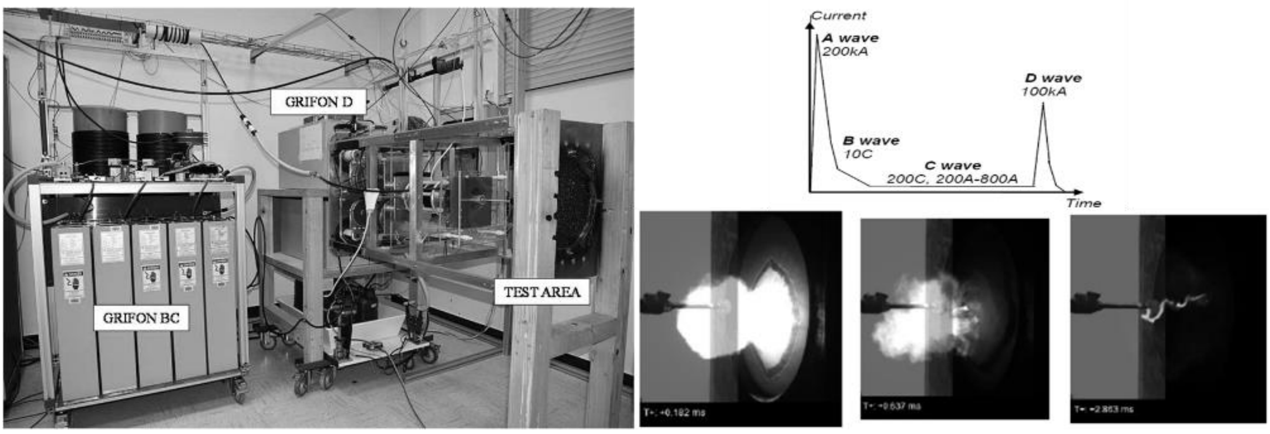

Figure 20 : Views of GRIFON Lightning strike test facility. Typical waves for Lightning strikes

For LTA systems, risk analysis shall differ from traditional aircraft because of the large dimensions of LTA vehicles and their low speed. Similar studies are conducted by ONERA on the fields of ESD and electromagnetic compatibility (indirect effects).

6.3. Icing

Icing conditions can produce accretions on specific areas of the airship [19]. This can generate additional weight than can modify the static heaviness, eventually change the center of mass if accretion occurs for instance at stern area Contrary to aircraft this shall not lead to catastrophic events but can still degrade flight performances. ONERA builds up a dedicated computations to estimate the accretion rates on airship hull or cable, for icing conditions relative to appendices C and O of DO160 regulation. These results contribute to overall design process, for gas management operational domain and for the need of ice protection or ice detection sensors.

6.4. Aerology

One of the main weakness of LTA systems is its extreme sensitivity to wind. ONERA elaborates a roadmap to investigate on this topic, in order to improve airship performances through wind conditions. The first aspect is to characterize realistic wind conditions. ONERA led dedicated meteorological studies, combined with Lidar wind measurement campaign. A probabilistic model of gusts was built, based on Karhunen Loeve development issued from a wind database [20][21]. Results from this model for parameters half wave length L/2 = 150m, Gust velocity Vgust 7.6m/s, Airship Velocity Vairship 100km/h are shown Figure 21. A comparison from mean horizontal real gust shape and the shape from regulation (Figure 9) exhibit strong differences.

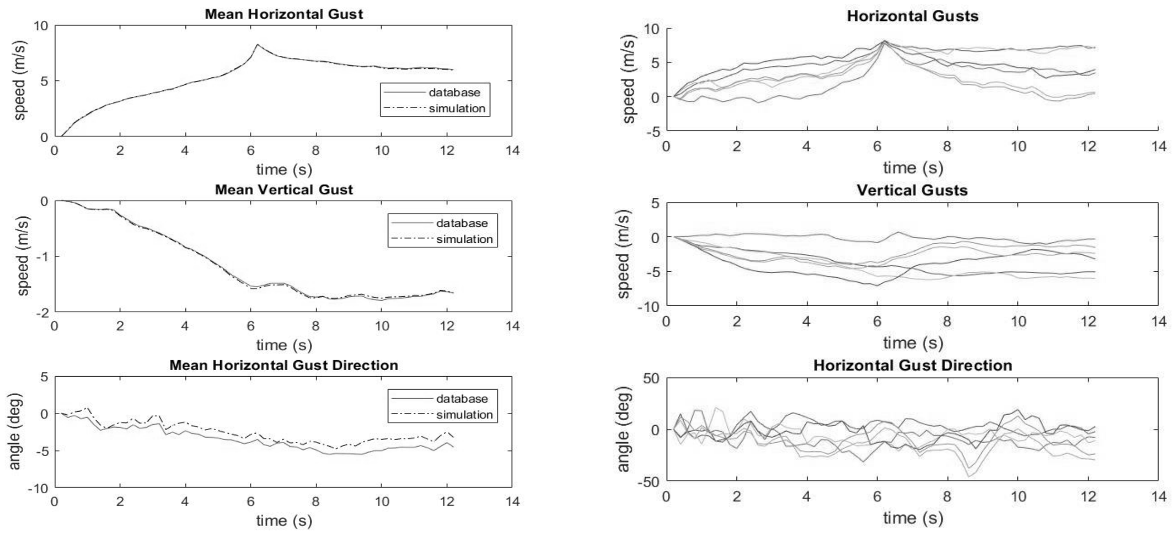

Figure 21: Results obtained from gust model (L/2 = 150m, Vgust 7.6m/s, Vairship 100km/h)
Left: comparison of mean gust characteristics simulation vs. database
Right: Ten samples of simulated gusts issued from gust model

The gust generator can then feed the aerodynamic gust model described in §4 to characterize the response of LTA system. Outputs can be used either for flight dynamics analyses, such as control laws improvement or for structural design assessment (for instance fatigue or aeroelastic issues).

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7. Conclusions and Perspectives

Lighter than Air (LTA) technologies are experiencing an important revival, which can be seen by the number of LTA programs currently in development worldwide. Two main applications are envisioned which are heavy lift transportation, and observation/ surveillance. Great perspectives are anticipated with the integration of recent technological breakthroughs.
ONERA has been working on LTA subjects for the last 10 years, collaborating with the main French actors of the domain. ONERA has been deeply involved in many aspects such as overall design, flight modeling, guidance/control laws, aerodynamics and more recently environmental conditions (lightning, EM Compatibility, icing, acoustics, aerology,…). The purpose of this article is to provide a comprehensive review of the main results achieved by ONERA.
ONERA has been involved in the flight modeling of LTA systems, using its own LTA flight simulation tool, including Guidance Navigation Control (GNC) module. This actually implies to model at proper level, besides traditional components of an aeronautical simulation, gas management systems with eventually thermal/thermodynamics aspects, ballast management, cables systems (for load transfer, tethered balloons…) and mooring systems. On GNC aspects, ONERA has developed dedicated laws (up to a Critical Design Review level) to address cruise phases as well as more specific hover or station keeping using more advanced techniques.
ONERA has developed hull aerodynamic models combining both experimental (wind tunnel) and numerical (CFD) approaches. ONERA led several wind tunnel campaigns within the frame of LTA programs including static and dynamic tests. LTA aerodynamics are indeed very specific because it is desirable to study the full domain of aerodynamic angles. Moreover, damping coefficients and added masses shall be assessed thoroughly. An innovative approach to set up a methodology to create an aerodynamic model that takes into account local spatiotemporal variations of airspeed has been validated. All these models are compliant with flight model so that dedicated research studies in guidance and control in closed loop as well as overall performances assessment can be conducted later on.
ONERA has added some research activities dealing with environmental conditions: Lightning Direct Effects, Electromagnetic compatibility, Icing and Meteorology. The goals are both to investigate on specific issues linked with LTA applications and to integrate the typical constraints linked with environmental conditions as soon as possible in the design process.
ONERA perspectives of work on LTA subjects are actually broad in direct continuation of what has been already accomplished. The next step is the validation and the calibration of these models with flight data, hoping that full-scale prototypes will fly in the near future.

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