EOLE, AN INNOVATIVE FLYING SCALE DEMONSTRATOR FOR AIR-LAUNCH-TO-ORBIT AUTOMATIC SYSTEMS

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Abstract

Onera and the French space agency CNES, in close collaboration, have been studying air-launch-to-orbit systems for many years now and have been promoting a two-vehicle concept where an unmanned dedicated carrier releases a launcher at predetermined separation conditions in terms of Mach number, altitude and slope angle.

Fully related to these studies, Onera and CNES lead the development of a flying scale automatic demonstrator, called EOLE, which aims to be an experimental platform for testing various launch conditions and separation technologies. EOLE's main objectives are to investigate the definition and the implementation of the launch separation conditions and to identify the relative behaviors of both vehicles (carrier and launcher) during the separation phase. These results will help calibrate models designed to analyze the separation on full-scale vehicles.

This paper presents the EOLE development program, its main experimental objectives and the critical problematic of results extrapolation toward full-scale vehicles.

1 Introduction

Air-launch-to-orbit systems have been investigated for the last years because of their potential advantages on classical ground-launch systems for space transportation and space tourism. Such concepts consist of a two-vehicle system where an aircraft-based carrier acts as the first stage of the launch system and releases a rocket at predetermined separation conditions in term of Mach number, altitude and slope angle.

Thanks to the kinetic and potential energies provided by the carrier, the rocket performances could be enhanced: the payload placed in orbit with a given rocket could be heavier or the rocket could be lighter for a given payload. In addition, the carrier flight capabilities offer a great flexibility of launch operations: the carrier can reach any orbital azimuth launch requirements and can join favorable meteorological conditions.

Besides the performances and operational benefits of such concepts, air-launch-to-orbit systems present economical gains thanks to the carrier reusability.

In order to improve the knowledge of air-launch-to-orbit systems, the Centre National d'Etudes Spatiales (CNES) and Onera have been leading the development of an innovative flying scale automatic demonstrator, called EOLE, which aims to be an experimental platform for testing various launch conditions and separation technologies.

2 CNES and Onera's air-launch-to-orbit systems feasibility analysis program

Considering their numerous potential benefits, CNES and Onera have set up a program aiming at studying several options of automated air-launch-to-orbit concepts, focused on small satellites launching in Low Earth Orbit (LEO) [1][2][3][4].

Because only few efficient commercial solutions exist for this particular class of satellites, CNES aims to get a well-argued verdict on the operational feasibility of small satellite launch concepts based on automatic air-launch-to-orbit systems.

Since 2005, CNES and Onera have been leading a proof of concept program and investigating several kinds of air-launch-to-orbit concepts in which the carrier is derived from a High Altitude Long Endurance (HALE) UAV.

The design process implemented is based both on Onera's experience in Multidisciplinary Design Optimization (MDO) methods and on a home-made MDO-based design tool dedicated to HALE UAV conceptual design. In such issues, MDO formulations are used both to define the optimum two-vehicle composite by managing the coupling design parameters and to design separately each of the two vehicles.

The first part of this program, called Dedalus project for DEsign of Dual-use Air-Launch-to-orbit UAV System, consisted in two sequential phases.

The first phase aimed to design an air-launch-to-orbit system able to place a 150 kg payload in the 800 km polar orbit. It leads to a 22t TakeOff Weight (TOW) composite consisting of a conventional HALE UAV carrier with two booms and two independent tails which releases in a 16 km altitude steady level flight a 13t winged launcher at Mach 0.8. The carrier has a 36m span swept high wing under which the launcher is handled between the two booms. Such configuration gives a sufficient free space for the launcher and allows locating the center of gravity of both vehicles at the strictly same position to keep the carrier controllability as well with and without launcher.

In this concept, the carrier is also able to achieve civil missions like cargo transportation or HALE UAV survey missions: it can carry 7t cargo 9000 km away or perform typical 24h survey mission at a flight altitude of 16 km with a stand-alone sensor bay. This multipurpose ability allows the economical viability of such an air-launch-to-orbit system by adding a rentable operational alternative to small satellite launching.

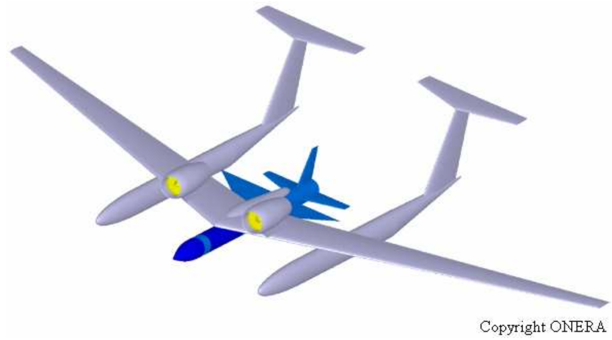

Fig. 1. Dedalus Phase I Air-launch-to-orbit Concept

Starting from the lessons learnt in the design and analysis of the previous configuration, the second phase of the Dedalus project consisted in extending the scope of the research with a parametric approach, aiming at defining the best compromise between the air-launch-to-orbit automatic system complexity and the ultimate performance: the satellite mass placed in orbit. One part of the work has been focused on the design methodology process. First, the models used separately for the carrier and the launcher were refined. Then, the interdisciplinary exchanges were favored in order to improve the composite system optimization. The other part of the work consisted in covering a wide range of system specifications in terms of operational objectives and design constraints:

- Considering the carrier development costs minimization as an objective, the use of an already existing HALE UAV was analyzed. Based on the RQ-4 GlobalHawk block 20, the airframe has been partially redesigned to carry a launcher and the operational air-launch-to-orbit capabilities were assessed. Due to layout difficulties to install a linear launcher under the fuselage, the possible launcher is only 2t in comparison to the potential 5t RQ-4 GlobalHawk block 20 payload. Released in steady level flight at Mach 0.6 / flight altitude 16 km, the linear launcher can place a 40 kg payload in 250 km polar orbit.

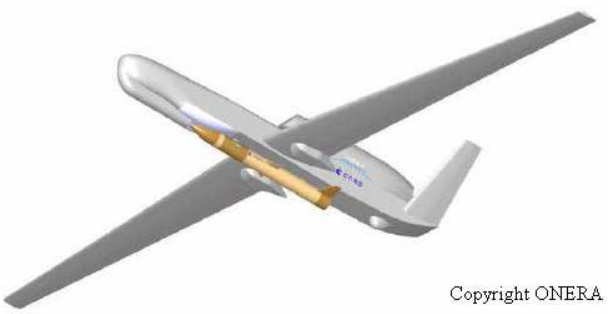

Fig. 2. Dedalus Phase II RQ-4 GlobalHawk Based Air-launch-to-orbit Concept with linear launcher

- An alternative solution has been investigated based on a 3 parallel stage launcher using lateral boosters in order to reduce its overall length. This launcher fulfilled the maximum payload capability and can deliver a 100 kg satellite in the same conditions as written above.

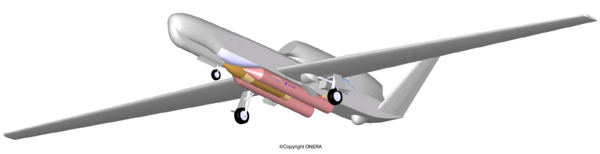

Fig. 3. Dedalus Phase II RQ-4 GlobalHawk Based Air-launch-to-orbit Concept with 3 parallel stage launcher

- Another solution dealt with the use of a dedicated HALE UAV solely designed for the air-launch-to-orbit mission. In that way, the operational objectives were refocused on placing 10kg nanosatellite in 250 km polar orbit. The corresponding air-launch-to-orbit system is a 3t TakeOff Weight (TOW) composite consisting of a conventional HALE UAV carrier with two booms and two independent tails which releases in steady level flight a 1.6t launcher at Mach 0.6 / flight altitude 12 km. Based on this reference concept, a parametric study has been performed considering two release altitudes (12 and 16 km), two payload weights (10 and 50 kg) and 3 targeted orbits (250, 500 and 800 km). In this parametric study, the release is no longer in steady level flight but can afford a slope angle up to 45°.

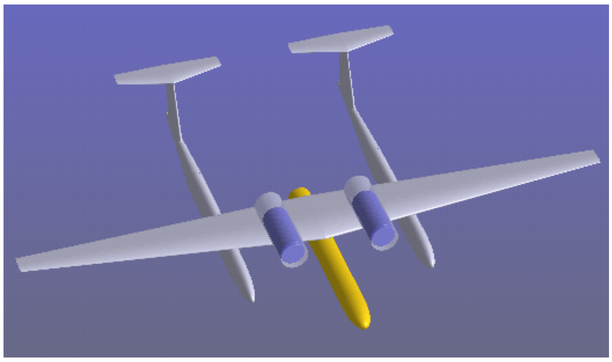

Fig. 4. Dedalus Phase II Nanosatellites Air-launch-to-orbit Concept

Following the Dedalus project, a second one called L3AR project for Lancement Assisté par Aéroporteur Automatique Réutilisable, was set up. Its purpose was the design of a dedicated air-launch-to-orbit system to place a 50 kg payload in 800 km Solar Synchronous Orbit (SSO). Two main new constraints were added: to reinforce the space specificity of the system in which the carrier design is strictly made in respect with its first stage launcher role, and to minimize the carrier development costs by sizing a low cost solution up. These specifications led to two different carriers able to release a 7.7t launcher at Mach 0.6 / flight altitude 14.7 km and a 40° slope angle:

- A conventional single boom either with one single jet engine leading to a 12.6t TOW composite or with two jet engines leading to a 13.8t TOW composite.
- A blended wing body either with one single jet engine leading to an 11.9t TOW composite or with two jet engines leading to a 12.9t TOW composite.

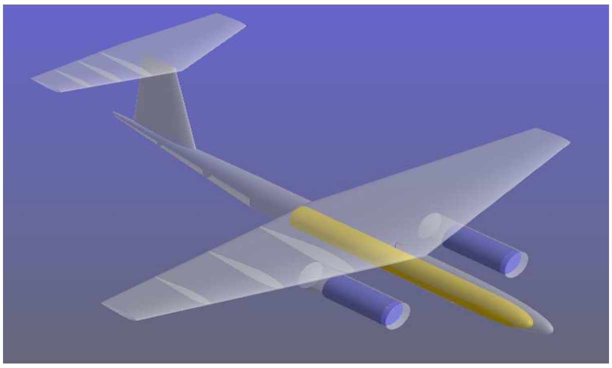

Fig. 5. L3AR Twin-Engine Single Boom Air-launch-to-orbit Concept

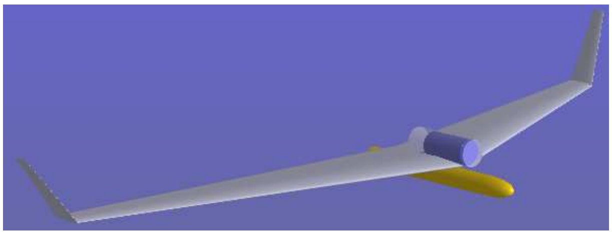

Fig. 6. L3AR Single-Engine Blended Wing Body Air-launch-to-orbit Concept

3 Motivations for building a flying scale demonstrator

The above mentioned conceptual studies suite has raised some technological issues that couldn't be solved in the scope of the proof of concept program.

First, the carrier and launcher separation conditions specifications have to be confirmed and the effects on the launcher performances of small perturbations and / or small deviations have to be quantified. These elements will take part of the launcher release sequence definition.

Then, the aerodynamic and inertial interactions that should occur during the beginning of the separation phase have to be better identified and quantified. This subject represents a quite original work because of the particular separation conditions specified in the designed air-launch-to-orbit concepts and the mass of each of the vehicles that tends to be equivalent.

Moreover, the release subsystem has to be specified regarding the separation conditions objectives. The main physical principles, the technological nature and the behavior of the release subsystem during the release phase represent critical elements to achieve the expected launcher separation conditions.

Facing these issues, a scaled demonstrator has appeared to be of great interest to help solving them, or at least reaching a better understanding of them. A preliminary study has investigated and confirmed this assumption and the setting up of an experimental demonstrator has been decided in 2008.

Called EOLE, this experimental vehicle aims to be a dedicated flying platform for testing various launch conditions and separation technologies in order to investigate and quantify the definition and the implementation of the separation conditions, the release subsystem, and to identify the relative behavior of the carrier and the launcher during the separation phase.

Similarly to the previous studied air-launch-to-orbit concepts, EOLE consists of a scale fixed-wing carrier aircraft able to perform automatic flights, thanks to automatic systems, in order to carry and launch potentially rocket powered and piloted scale space launchers. It aims to reproduce the dynamic phenomenons that occur during the carrier and launcher short-lived separation phase.

All the knowledge capitalized through the use of EOLE flying demonstrator will help calibrate models designed to analyze the separation on full-scale vehicles.

4 EOLE characteristics and peculiarities

4.1 EOLE development particular process

The EOLE development program takes place in the scope of the Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique (PERSEUS), implemented and funded by CNES. PERSEUS aims at developing and testing some potential technologies for future launchers, involving students in every aspect of projects, from preliminary studies to flight experiments [5][6].

EOLE is one of the major projects of PERSEUS, and as a consequence, its development involves students in technical topics by the way of internal projects in several universities or national Colleges of Engineering and internships. This particular process sets up a real and strong collaboration between engineers, researchers, professors and students from the involved establishments.

In addition, EOLE is not only a flying demonstrator of future full-scale air-launch-to-orbit carrier, but also a flying platform able to carry some scientific experiments coming from student teams involved in other PERSEUS projects. That leads to some requirements regarding EOLE operational costs which have to be mastered.

In the EOLE development program, CNES acts as the prime contractor and is directly linked with all the involved partners.

Onera, as the project manager, coordinates the program for CNES, manages the partner's activities and performs technical analysis and investigations focused on the carrier EOLE.

Aviation Design, a specialized SME in UAV prototypes, is in charge of the overall design and manufacturing of the carrier EOLE and will perform the on-going flights.

Then, Planète Sciences, the Institut Polytechnique des Sciences Avancées (IPSA) and the Ecole Centrale Lyon (ECL), a student space association and two colleges of engineering, design and build the standard scale launcher ARES [7].

Finally, University of Evry Val d'Essonne (UEVE), is in charge of the design and manufacturing of the standard release subsystem.

The EOLE program development has been divided in two main phases.

From March 2009 to September 2010, the preliminary design of the demonstrator was done by a very close team composed of Onera's and Aviation Design's engineers. This first part, which froze the EOLE architecture and assessed the main performances, has led to the CNES's decision to launch the EOLE development program under the leadership of Onera.

The present and second main phase has started in September 2010. This phase includes the detailed design of airframe and onboard equipments, the overall manufacturing of the demonstrator and is moving toward the flight tests. They will qualify the demonstrator as a flying experimental platform dedicated first to test several separation flight maneuvers and several release subsystems.

The first flights are planed at the beginning of 2013 and the qualification of the demonstrator as an experimental platform is expected in 2014.

4.2 EOLE main characteristics

EOLE is a fixed-wing carrier aircraft [10]. Its architecture has been strongly inspired by the previous full-scale air-launch-to-orbit concepts: the two booms and two independent tails airframe gives a sufficient free space to install the launcher between the booms. The central pod presents a great modularity and its standard flat interface can accommodate various release subsystems. The central position of the launcher is specified in order to locate the center of gravity of both carrier and launcher at the strictly same position in order to ensure the carrier controllability as well with and without launcher.

The V-frame of the tails contributes to give some free space to the launcher in the vicinity of the EOLE carrier. It reduces the launcher / tail collision risks during the beginning of the separation. It avoids also the tails thermal exposition from turbojet engines, which are located on the upper side of the wing to get free space for the launcher, and from launcher's thruster earlier ignition.

Fig. 7. EOLE Development Program Chronology

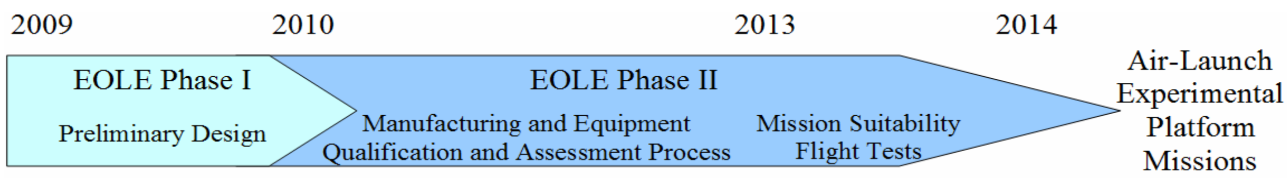

Fig. 8. CAD View of EOLE demonstrator with launcher

Expected to be used as a flying experimental platform, EOLE offers a great modularity with numerous interchangeable elements:

- In order to locate the launcher either at the lower surface or at the upper surface of the wing, the central part of the vehicle has been designed to be movable. Only the lower surface launcher mounting is presently available; a second one, able to mount the launcher at the upper surface, should be manufactured in a future upgrade of the experimental system.
- Outer wings are also movable in order to adapt the wing loading. This opportunity increases the range of the represented full-scale carrier. The design and the manufacturing can sustain future new external wings too.

To achieve the launcher release within the most accurate conditions, EOLE is an automatic vehicle. Except during take-off and landing phases, all the flight is managed through an autopilot using mainly hybrid IMU + GPS devices, and, particularly, the specified separation sequence occurs automatically once the order is sent by the ground station.

EOLE typical main performances (at 150 kg)	
Max endurance	90min at 4000m
Max range	250km at 4000m 200km at 2000m
Max true air speed	390 km/h at 0m
Operational ceiling	6000m

EOLE main characteristics	
Weights	
Equipped Empty Weight	107 kg
Max. Take-Off Weight	150 kg to 200 kg
Max. Payload Weight	50 kg
Max. Fuel Weight	34 kg
Dimensions	
Wingspan	6.7 m
Length	3.3 m
Height	1.4 m
V-tails (in 2 parts)	55.5° dihedral
Motors	
2 x AMT Titan turbojets	2 x 40 daN
Wing characteristics	
Reference area	$2.57m^2$
Aspect ratio	17
Onera's OAPV15i and OAPV13i airfoils	

5 EOLE development process

As explained before, each partner is in charge of designing and manufacturing one of the three elements which compose the experimental air-launch-to-orbit system and Onera manages the overall technical activities for CNES: Aviation Design is in charge of the carrier EOLE, Planète Sciences, IPSA and ECL are in charge of the standard launcher ARES and UEVE is in charge of the standard release subsystem.

To succeed and ensure the EOLE experimental platform safety and durability, Onera performs as well technical analysis and investigations focused on the carrier.

Onera studies the structural behavior of the carrier EOLE, under static and dynamic loads, combining FEM simulations and structural tests:

- Wing static bending strength tests and V-tail static strength tests took place at ISAE Toulouse (France), in two steps, including 11 students in the setting up and management of the experiment.
- The overall dynamic tests, including reference launcher, are performed in the Onera's dynamic test facilities in Meudon (France) in order to assess the flutter characteristics.

Then, Onera performs all the activities that will qualify the ability of the EOLE carrier to fly safely according to flight test center requirements and will prepare the future launch experimentations (performance assessment, flight tests specifications, etc.).

Fig. 9. EOLE Flutter Tests (Onera)

In order to estimate EOLE’s aerodynamic performances, Onera has performed numerical CFD simulations and wind tunnel tests. A 1/2.3 scale model has been manufactured, instrumented and set up in the wind tunnel L2, in the Onera’s center of Lille (France). Wind tunnel tests cover all the required aerodynamics coefficients and derivatives for both EOLE alone and carrying a reference scale launcher. In addition, the separation phase is analyzed with numerical CFD simulations which are focused on the launcher behavior assessment in the vicinity of EOLE.

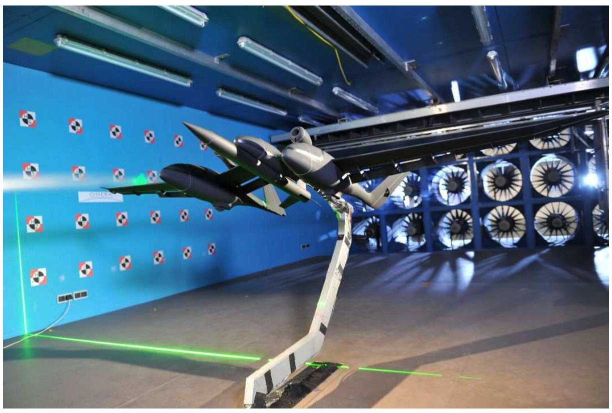

Fig. 10. EOLE model Wind Tunnel Tests (Onera)

Regarding the separation maneuvers, Onera defines robust maneuvers guidance and control laws that will be implemented in EOLE's autopilot. Then, a training flight simulator is under development to validate EOLE's behavior and performances, to check the guidance and control laws and to replay the specified missions.

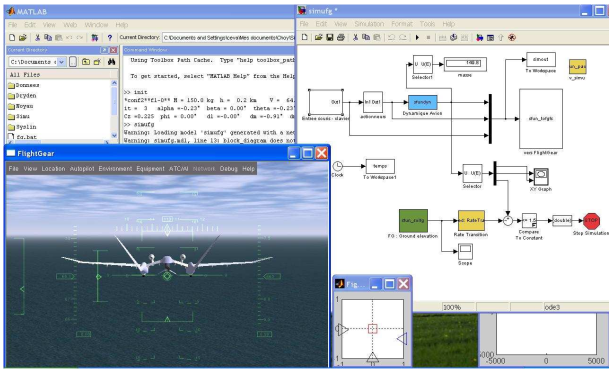

Fig. 11. View of the Onera's flight simulator

Several formal milestones are planned to validate the airframe and avionics manufacturing, to ensure the compatibility of the three elements of the composite air-launch-to-orbit experimental platform, to validate the safety assessment, and to validate the flight test organization, management, and security rules for safety decisions. These milestones will lead to the flight clearance for the air-launch-to-orbit mission suitability flight tests that will qualify the composite for its future experimental platform use.

Finally, as a guideline of the demonstrator development, a PhD thesis which focuses on the separation phase analysis is in progress to build a conversion methodology for the air-launch-to-orbit experiments that will be performed with the demonstrator. The analysis aims at finding criteria that best express the phenomenon at stake during the separation phase (effects of steady or unsteady aerodynamic conditions, mass and inertia of the vehicles, dynamic response to perturbations, dynamic coupling between both vehicles…) and way of translation to full scale vehicles. The interactions between the carrier, the launcher and the release subsystem will then be studied in more details.

6 Experimental air-launch-to-orbit flight tests

Used as an experimental air-launch-to-orbit flying platform, the carrier EOLE is designed to be equipped with various release subsystems and launchers. Currently the development process is focused on only one standard release subsystem and one standard launcher but it will carry and release numerous others as defined in its top level requirements. The maximum payload weight is 50 kg, considering 10 kg for the release subsystem and 40 kg for the launcher. The standard release subsystem is 3.1 kg and the standard launcher ARES is 10 kg. The payload capability seems to be sufficient to cover a wide range of future tested concepts.

The specified launch mission aims to reach the altitude of 4000m at Mach 0.2, and to start the automatic drop maneuver which can be:

- a steady level flight launch,
- a 45° slope angle launch during a 3g pull-up maneuver starting at Mach 0.3.

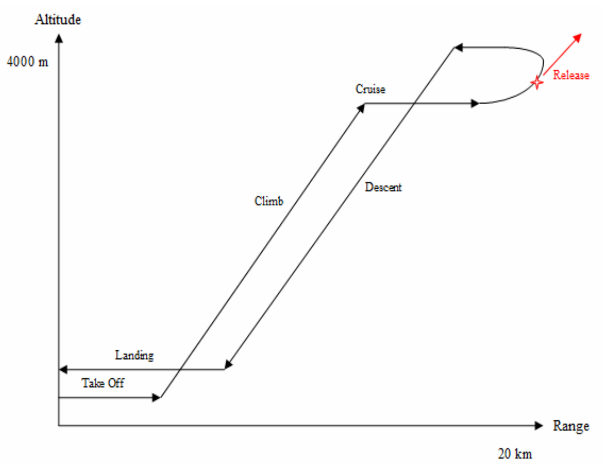

Fig. 12. Typical Air-launch-to-orbit Mission Profile (with 3g pull-up maneuver)

EOLE standard air-launch-to-orbit mission profile (with 3g pull-up maneuver)				
Phase	**Speed**	**Altitude**	**Duration**	**Distance**
T-Off	35m/s	0m		0 km
Climb	55m/s	0→4000m	7 min	0→20km
Cruise	65m/s	4000m	1 to 10min	20km
Release	**90m/s**	**4000m**	**1 min**	**20 km**
Descent	80m/s	4000→0m	5 min	20→0km
Landing	30m/s	0m		0km

7 Flight test result based lessons and translation toward operational concepts

The future EOLE based air-launch-to-orbit experiments will focus on the dynamic phenomenon that occur during the launcher and carrier separation phase. The main problematic concerns the extrapolation of both scale vehicles relative movements to full-scale vehicles. Such problematic requires similitude area knowledge which expresses scaling relationships. A PhD thesis is dedicated to analyze the way of translation of scale experimental measurements toward full-scale vehicles.

When the similitude theory is applied, the variables at a certain scale can be extrapolated at another scale with simple proportional relations. However, the application of the similitude theory is associated with very restrictive constraints. Indeed, different non-dimensional factors based on the system's variables have to be kept constant from a scale to another. These non-dimensional factors are deduced from the application of Vaschy-Buckingham theorem to the equations governing the studied motions. In aeronautics, two motions are studied: the motion of the fluid and the motion of the flying body. The former one is governed by Navier-Stokes equations. The latter one is governed by the equations of force and moment of the flying body. The non-dimensional factors represent the participation of a certain kind of force in the studied motions.

In aerodynamics, which studies the motion of the fluid, the Reynolds number represents the participation of the viscous forces. It is certainly of interest during the separation:

$$\mathrm{Re} = \frac{fluid's\,inertial\ forces}{viscous\ forces} = \frac{\rho V l}{\mu} \qquad (1)$$

with ρ the fluid mass density (kg/m^3), V the vehicle velocity (m/s), l the characteristic dimension (m) and μ the absolute fluid viscosity (N.s/m^2).

The Mach number represents the participation of the pressure forces and will be ignored as the flights are subsonic. The Froude number represents the participation of gravity and is generally not used in aerodynamics. However, the Froude number also represents the participation of gravity in the motion of the flying body. It is then of major interest:

$$Fr = \frac{inertial\ forces}{gravitational\ forces} = \frac{V^2}{\lg} \qquad (2)$$

with V the vehicle velocity (m/s), l the characteristic dimension (m) and g the acceleration of gravity (m/s^2).

The equations governing the motion of the flying body also lead to another non-dimensional factor that takes the form of a mass ratio. It represents the participation of the aerodynamic forces:

$$\frac{m}{\rho l^3} = const. \qquad (3)$$

with m the vehicle mass (kg), ρ the fluid mass density (kg/m^3) and l the characteristic dimension (m).

Reynolds and Froude numbers can be kept constant from the small scale of EOLE to the final large scale.

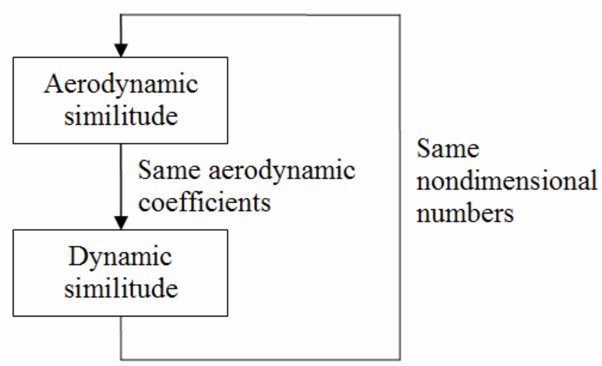

Fig. 13. Similitude Process

However, the mass ratio is very different at the two scales. The carrier and the launcher should weight approximately fifteen times more in order to keep the mass ratio constant. Moreover, even if the carrier and the launcher could weight more, the mass of the final full scale system can be roughly estimated but its actual value is not known. Because the mass ratio cannot be kept constant from one scale to another, the participation of the aerodynamic forces in the motion of the flying body is different. A different participation of the forces leads to a different motion which also contributes to change the forces based on the state of the flying body, like the aerodynamic forces. Thus, the motion gets more and more different at the two scales. The extrapolation cannot be as direct as it would be in the case of dynamic similitude.

If the participation of the aerodynamic forces is not the same, it can be imagined that it may not be necessary to respect Froude that represents the participation of the gravity. Depending on Froude being respected or not, the motion is expected to be different. However, respecting Froude leads to similar characteristics. For example, if Froude is respected, the frequency of the short period oscillation of the flying system is correct. Indeed, it does not depend on the mass.

The constraints of the similitude theory are often hard to respect. The notion of quasi-similitude has sometimes been used when they could not be totally respected. A method to solve quasi-similitude problems with so-called prediction factors can for example be found in the Air Force archive [8]. However, an analysis of this method showed that it needs to be carefully assessed to decide on its use in this study.

The similitude study will then be focused on particular aspects of the separation. The aerodynamic interactions could have been of special interest. The aerodynamic interactions are generally measured through the aerodynamic coefficients of the aircraft and the launcher [9]. However, CFD calculations tend to prove that these interactions will be very low after the release of the launcher. Their role is then limited and their estimation and extrapolation would be very difficult because of the similitude problems and an important uncertainty on measurements.

Other aspects of this original separation are now analytically studied in order to prepare new measurements and extrapolation. Control aspects will be particularly studied.

8 Conclusion

EOLE development program is currently in progress: it has begun in 2009 and is expected to end in 2014 with the experimental platform qualification.

Up to now, the manufacturing of the carrier is over. On board equipment is almost manufactured and integrated but some elements have still to be implemented.

In addition, the standard release system and launcher manufacturing are over and their equipment remains to be done.

The work is now focusing on the carrier qualification process and its performances assessment. Then, the air-launch-to-orbit mission suitability flight tests specification is in progress.

Finally, the PhD, focused on the transposition method from EOLE to full scale system, will progress and will use as much as possible first experimental flights as input data for validation or at least method calibration.

The project will provide an effective and flexible innovative experimental platform, for testing various air-launch-to-orbit conditions and separation technologies, supported with an argued conversion methodology to full-scale vehicles.

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