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Analysis and optimization of an air-launch-to-orbit separation

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ABSTRACT

In an air-launch-to-orbit, a space rocket is launched from a carrier aircraft. Air-launch-to-orbit appears as particularly interesting for nano- and microsatellites which are generally launched as secondary loads, that is, placed in the conventional launch vehicle's payload section with a larger primary satellite. In an air-launch-to-orbit, a small satellite can be launched alone as a primary load, away from a carrier aircraft, aboard a smaller rocket vehicle, and in doing so, benefit from more flexible dates and trajectories. One of the most important phases of the mission is the separation between the carrier aircraft and the space rocket. A flight simulator including a large number of factors of uncertainties has been especially developed to study the separation, and a safety criteria has been defined with respect to store collision avoidance. It is used for a sensitivity analysis and an optimization of the possible trajectories. The sensitivity analysis first requires a screening method to select unessential factors that can be held constant. The Morris method is amongst the most popular screening methods. It requires limited calculations, but may result in keeping constant an essential factor which would greatly affect the results of the sensitivity analysis. This paper shows that this risk can be important in spite of recent improvements of the Morris method. It presents an adaptation of this method which divides this risk by a factor of ten on a standard test function. It is based on the maximum of the elementary effects instead of their average. The method focuses the calculations on the factors with a low impact, checking the convergence of this set of factors, and uses two different factor variations instead of one. This adaptation of the Morris method is used to limit the amount of the air-launch-to-orbit simulations and simplify the uncertainty domain for analysis by Sobol's method. The aerodynamic perturbations due to wind, the parameters defining the trajectory, the interactions, and the mass characteristics of the systems are detected as factors with a high impact. The parameters of the trajectory are finally optimized with a stochastic gradient method. It shows that the separation is safer with a low speed, a low climb angle, and a high vertical acceleration of the aircraft. A trajectory offering such a separation will be tested with an air-launch-to-orbit demonstrator from the French space agency CNES and the French aerospace laboratory ONERA.

1. Introduction

Nano- and microsatellites usually have access to space as secondary loads, that is in the same space rocket as a larger satellite called the primary load. It can result in important constraints for these satellites as this kind of launch is optimized for the primary load. Thus, there is a growing interest for air-launch-to-orbit systems dedicated to these types of satellites. While space rockets are generally launched from a spaceport like the Guiana Space Center, an air-launch-to-orbit system is based on a carrier aircraft which jettisons the space rocket at a certain altitude. Such system can offer more flexible launch dates

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Fig. 1. Flight of the demonstrator EOLE.

and trajectories to nano- and microsatellites. Moreover, it also leaves the lower, dense region of atmosphere more efficiently than a classical launch. Several systems of this kind are currently under study. The French space agency has worked on a system based on the Rafale fighter [1], the Pegasus NASA program has already proceeded to launch several small satellites [2] while the American defense agency DARPA explores new possible designs [3], and Virgin Galactic intends to develop an air-launch-to-orbit system in the field of space tourism [4]. The work presented in this paper is part of a technical study of the French space agency CNES and the French aerospace laboratory ONERA on a new air-launch-to-orbit system. It is related to the Perseus program [5] and follows the development of the demonstrator EOLE, shown in Fig. 1.

The separation between the carrier aircraft and the rocket is a particularly sensitive phase with numerous complex dynamics and large parameter variations. Such variations modify the trajectories of both the carrier and the rocket and may put at risk the integrity of each vehicle. Quantification of the safety of the separation can be estimated using a performance function. The global probability that the separation fails has been estimated with Monte-Carlo simulations for two-stage reusable launch vehicles [6]. The study of these reusable launch vehicles highlighted the importance of the determination of the impact that the values of the different parameters could have. This determination, which was based on very limited number of cases, is deepened for the demonstrator EOLE. It first requires to formally associate its parameters to uncertainties. Various uncertainties are being taken into account, from the mass to the opening time of the hooks between the aircraft and the launcher, and to the aerodynamic interactions. The aerodynamic interactions are transient dynamics which are hard to predict [7]. Such transient dynamics are now a topic of particular interest. For example, their study now permits a better modeling of rotor aerodynamics [8] and of insect flapping flights [9]. Showing that the uncertainties on the aerodynamics interactions influences the performance function would plead in favor of further research on these transient dynamics. As no analytical expression can be derived linking the safety criterion to the flight characteristics, the criterion is evaluated using a dedicated flight simulator representing the demonstrator trajectory during and after separation.

Sensitivity analysis is a practical tool to determine the sources of uncertainty that will strongly impact on the variability of an output function reflecting the behavior of a complex system [10]. It is first necessary to determine the set of variables, known as uncertainty factors, which are subject to unknown variations and which play a role in the resulting value of the performance criterion. The sensitivity analysis can then define the relationship between the variability of the performance function and the variability of the uncertainty factors. A factor is said to have a high influence if a small variation of this factor leads to a large variation of the performance criterion.

Sobol's method is widely used in sensitivity analysis as it can provide accurate results [11]. However, as the number of uncertainty factors is rather large, the computational burden required by this approach would not make it possible to perform an accurate sensitivity analysis. For such a combination of large number of uncertainty sources and a rather long time of process simulation, a screening approach is typically used first to identify the factors which can be set to a given value so as to perform the sensitivity analysis on a reduced set of uncertainty factors. This step is generally referred to as factors fixing. Thus, in this work, a factor is described as fixed when it is set to a constant value. A screening method provides qualitative results with a limited number of calculations. The Morris method is among the most popular screening methods. It was initially developed in 1991 [12], and it gained in popularity ever since [13]. The Morris method estimates the importance of the factors by averaging the results of One-factor-At-a-Time (OAT) variations in a discrete hypercube.

The selection of the uncertainty factors that can be held constant is a very important step. It is described as *one of the major settings of global sensitivity analysis* in [14]. Indeed, the relative impact of an uncertainty factor on the variation of the performance criterion can be underestimated at first and thus the variable may be set to an a priori value, e.g. its mean value. The estimation of the variability of the obtained criterion would then be erroneous. Underestimating a factor influence using the Morris method may be due to three reasons.

First, the Morris method is based on different arbitrary choices. For example, the number of times each factor is varied is set a priori, and is often chosen very low. Indeed a screening method is expected to require a limited number of calculations. The factors to be held constant are also generally arbitrarily chosen, without particular criteria.

A second point is that the benefit of performing more evaluations of the criterion with different values of the uncertainty factors, which directly infer the robustness of the sensitivity results, proves difficult to predict. Two approaches could be considered for that purpose but they are difficult to adapt to the Morris method. The verification of the convergence, used in [15,16], has two major limits. It is normally adapted to large samples while the Morris method only uses a few elementary effects for each factor, and the criteria defining whether the convergence has been reached or not is arbitrary. A bootstrap, as in [16], can provide confidence intervals for the relative impact of each factor. However, a bootstrap only relies on the elementary effects which have already been obtained, and if low values have been obtained for a factor which is actually important, the bootstrap cannot identify it as a problem.

Finally, the Morris method is generally used in its original form based on the random sampling of so-called trajectories [13]. It has been demonstrated that using radial points instead of trajectories, and a Latin hypercube sampling instead of a random sampling, improves the efficiency of the Morris method [17].