

Multidisciplinary Design Optimization of Sounding Rocket Fins Shape Using a Tool Called MDO-SONDA

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Abstract: *Multidisciplinary design optimization is a promising field in aerospace engineering. However, advances in this field have not been applied yet to improve Brazilian sounding rockets, such as the VS-40. Therefore, to give a perspective of the multidisciplinary design optimization in this context, this work presented a case study of this rocket, which consists of the shape optimization of its fins. To achieve this goal, a special tool called MDO-SONDA, which is the main contribution of this work, was developed. Its current version interacts with two high-fidelity executable codes, one of aerodynamics and another of trajectory, exploiting the synergy between both disciplines. The MDO-SONDA is based on a multiobjective genetic algorithm whose real operator was originally designed in this work. By using the proposed tool, it was found that the drag due to the rocket fins could be reduced up to 29% without increasing the chances of adverse effects that could lead to unstable behaviors.*

Keywords: *Sounding rocket, Rocket fin design, Multidisciplinary design optimization, Multiobjective genetic algorithms.*

INTRODUCTION

At the end of the 1990s, among the Brazilian sounding rockets, the VS-40 was presented as one that provides the best conditions for experiments in microgravity (Ribeiro, 1999). Space systems are complex, i.e., their behavior is governed by many distinct but interacting physical phenomena, and multidisciplinary, requiring balance among competing objectives related to safety, reliability, performance, operability, and cost (Rowell and Korte, 2003). Over time, advances in the engineering of complex systems have allowed to more quickly identify feasible solutions and exploit the synergy among the design disciplines (Rowell and Korte, 2003). However, the VS-40 has not been benefited by such advances yet. The interactions between the design disciplines of the VS-40 were processed in a sequential order, in which those disciplines that act early in the conceptual design establish constraints on the others that follow later, leading to a concept without regarding the trade-offs that may exist between the design objectives. The plausible consequence of such sequential methodology is a suboptimal design with

respect to the entire project, promoted by low synergy between the design disciplines.

Since 1993, when the first VS-40 was launched, the methodology that allows exploiting the synergy between its design disciplines has not been used yet for Brazilian sounding rockets. A methodology called multidisciplinary design optimization (MDO) replaces the traditional sequential methodology by synergic interactions between the design disciplines, promoting the overall gain in product's performance, decreasing the design time (Floudas and Pardalos, 2009).

Why should the VS-40 be revised? It promises the best conditions for microgravity experiments, but not widely launched yet such as the VSB-30, also a Brazilian sounding rocket, so that it could be more studied, and perhaps improved by considering collected flight data. The VS-40 was recently modified at the German Aerospace Center (DLR) in order to provide the required stability for a specific mission, because it was not originally designed for carrying a payload with exposed canards, indicating that its design can be altered, if necessary, to benefit its stability and, perhaps, its performance. Lastly, it has not been benefited by advances in the engineering of complex systems, and it may have some subsystems that could be improved regarding its next launches at Brazilian

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territory carrying the Sub-orbital SARA, a Brazilian platform for microgravity experiments.

Motivated by a search for VS-40 improvements, the use of the MDO was introduced in Brazilian sounding rockets. Therefore, the objective of this paper was to provide a perspective of the MDO application in this context based on a case study of the VS-40. As case study, the shape optimization of the VS-40 fins was proposed in order to improve its performance by reducing the drag due to the fins, without increasing the chances of adverse effects that could lead to unstable behaviors. To perform the optimization, a computer tool called MDO-SONDA (MDO of Sounding Rockets), which was developed by Alexandre Nogueira Barbosa, was used. MDO-SONDA presentation in the literature was first introduced by this paper.

SOUNDING ROCKETS AND MICROGRAVITY ENVIRONMENT

Sounding rockets, such as the VS-40, are characterized by their application and flight profile. According to Montenbruck *et al.* (2001), such rockets are constituted of solid fueled motors and a payload that carries instruments to take measurements and perform scientific experiments during a parabolic flight. Thus, the sounding term means taking measurements.

In comparison with the VSB-30, the VS-40 bi-stage can provide a wide exposure to the microgravity environment, characterized by a condition where an object is subjected to a g-force less than $10 \mu g$ (La Neve and Corrêa Jr, 2001), achieved by moving in free fall, where there are no forces other than gravity acting on the object.

Payloads carried by rockets achieve the microgravity environment after the burnout of the rocket when the thrust force is zero and the payload is above the atmosphere. It is assumed that the Kármán line, at 100 km above the seawater surface, might be used as a reference for microgravity experiment purposes to define the boundary between the atmosphere and the outer space, from which the atmosphere becomes so thin that the drag force could be neglected.

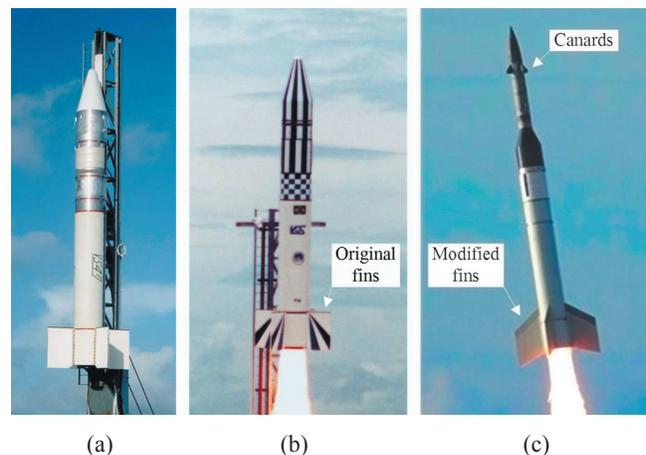
FACTS ABOUT THE VS-40

In spite of the fact that the VS-40 provides more exposure to microgravity than the VSB-30, since the 21st century began, rather than the VS-40, the VSB-30 has been most frequently used for microgravity experiments (Garcia *et al.*, 2011). Certainly, because the VSB-30 has met mission requirements

for microgravity experiments with an advantage, the payload recovery operation associated with the VSB-30 is less costly than with the VS-40, whose splashdown is approximately five times more distant from the continent-ocean boundary than the VSB-30, demanding more autonomy for the recovery means.

From 2004 to 2010, ten VSB-30 campaigns were successfully performed, three of them in the Brazilian territory (Garcia *et al.*, 2011). In contrast to the VSB-30, three VS-40 campaigns has occurred so far, two of them in the Brazilian territory, the first one in 1993, Santa Maria campaign (Fig. 1a), and the second one in 1998, Livramento campaign (Fig. 1b), both at the Alcântara Launch Center (CLA) in Maranhão (IAE, 2012). On June 22, 2012, a modified VS-40 called VS-40M, carrying the Sharp Edge Flight Experiment (SHEFEX) II (Weihs *et al.*, 2008a), a German project, was successfully launched at the Andøya Rocket Range in Northern Norway (DLR, 2012), and it became the first VS-40 operation in another country (Fig. 1c). The VS-40M fins shape (Fig. 1c) is significantly different from the two previous VS-40 (Figs. 1a and b). The new fins were designed and constructed for SHEFEX II at DLR due to the need of extended fins to compensate for the aerodynamic effects of the small canards at the payload, as can be seen in Fig. 1c (Weihs *et al.*, 2008).

In 1997, a recovery orbital platform called SARA for supporting short-orbital experiments in microgravity environment was proposed (Moraes and Pilchowski, 1997). In comparison with a sub-orbital flight, which provides a few minutes of microgravity conditions, an orbital one can provide more than ten days before reentering the Earth's atmosphere. The Space Capsule Recovery Experiment (SRE), which is an Indian spacecraft first launched in 2007, is a very



Sources: (a) and (b) Institute of Aeronautics and Space, Brazil; (c) DLR (2012).

Figure 1. VS-40 launches.

similar example of such a kind of platform (Reddy, 2007). Also, an example is the REX-Free Flyer, the German proposal for application of SHEFEX derived technology, which is a reusable orbital return vehicle for experiments under microgravity conditions (Weihs *et al.*, 2008b).

Thereafter, a platform called Sub-orbital SARA, which is part of the road map to achieve the orbital mission purpose of this platform, has been constructed to be launched by a VS-40, supporting an experimental module to be exposed to microgravity environment (La Neve and Corrêa, 2001).

The VS-40 was originally designed for flight qualification of the S44 motor, which constitutes the fourth stage of the Brazilian launch vehicle (VLS-1) (Pereira and Moraes Jr., 2000). In 1993, when the first VS-40 was launched, the MDO methodology had recently been presented.

The shape optimization of the VS-40 fins will be presented as a case study using such methodology to demonstrate its application in the context of Brazilian sounding rockets. However, before presenting the results of the optimization, the main aspects of the MDO-SONDA will be further depicted.

MULTIDISCIPLINARY DESIGN OPTIMIZATION OF SOUNDING ROCKETS

The MDO-SONDA was conceived to exploit the synergy between the design disciplines of sounding rockets. Among them, those that use physics-based engineering models are: propulsion, aerodynamics, heating, structures, controls, and trajectory. Its current version interacts in batch mode with two high-fidelity executable codes, one of aerodynamics and another of trajectory. Thus, it can exploit the synergy between these two disciplines. Interacting with at least two disciplines makes the MDO-SONDA able to demonstrate the MDO methodology. Besides, it can support multiobjective problems. It can also investigate the trade-offs between the design objectives.

The current version is only prepared for optimization of the shape of rocket fins. However, it is an object-oriented code written in C++ that provides specific forms, classes and objects to structure proper interfaces for further studies, including the shape optimization of other rocket subsystems, such as additional set of fins, nose fairing, protuberances and conical transitions between rocket stages of different diameters.

The main aspects of the MDO-SONDA are architecture, inputs, outputs, optimization algorithm, and how to proceed with the optimization.

Architecture

The architecture of the MDO-SONDA is described in two parts: the interaction between the objective function and two high-fidelity executable codes, one of aerodynamics and another of trajectory (Fig. 2a); and, the interaction between the optimization algorithm and the objective function (Fig. 2b).

The high-fidelity executable codes are: missile datcom and rocket simulation (ROSI).

The missile datcom is a widely used semi-empirical aerodynamic prediction code, which estimates aerodynamic forces, moments, and stability derivatives for a wide range of missile configurations as a function of three atmospheric descriptors: Mach number, altitude, and angle of attack (Sooy and Schmidt, 2005). Its original version was developed in FORTRAN 77 by the McDonnell Douglas Corporation. Later, the FORTRAN 90 version was documented by the U.S. Air Force (Blake, 1998).

The ROSI is also a FORTRAN code. It computes the motion of a rigid body in a three-dimensional space, considering also its rotation in yaw, pitch, and roll axes (Ziegltrum, 1984; Gomes, 2004). Its original version was developed by DLR (Ziegltrum, 1984). Since the 1980s, the ROSI has been successfully used for the trajectory calculation of Brazilian sounding rockets.

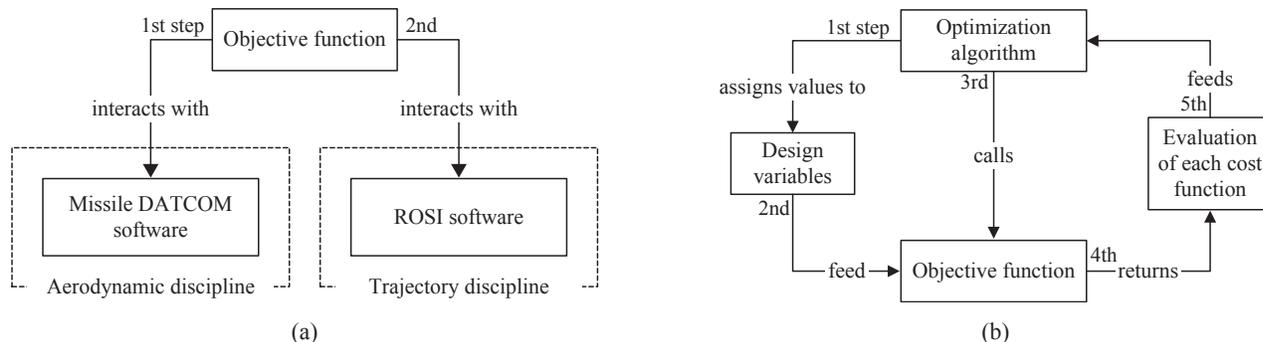


Figure 2. Interactions of the MDO-SONDA.

The MDO-SONDA calls the executable codes in batch mode, which means to run to completion without manual intervention. The missile datcom provides to ROSI the following aerodynamic properties: drag coefficient (C_D), normal force coefficient derivative with angle of attack ($C_{N\alpha}$), pitching moment coefficient derivative with angle of attack ($C_{M\alpha}$), pitching moment coefficient derivative with pitch rate (C_{Mq}), rolling moment coefficient derivative with roll rate (C_{lp}), and center of pressure (X_{cp}).

In addition, ROSI uses the roll driving coefficient ($C_{i\delta}$). C_{lp} and $C_{i\delta}$ are parameters of each single fin to determine the roll rate of the rocket. Unfortunately, the missile datcom does not provide $C_{i\delta}$, but provides the rolling moment coefficient (C_l). To use missile datcom calculation indirectly, it is assumed that C_l for a very small deflection angle of each fin, $\delta=0.01^\circ$, can be used to estimate $C_{i\delta}$ (Eq. 1):

$$C_{i\delta} = \frac{\partial C_l}{\partial \delta} \cong \frac{C_l}{0.01^\circ} \quad (1)$$

The MDO-SONDA manages the process of each executable code, writes their inputs, and reads their outputs, coordinating their interaction. During the optimization loop, if they freeze for any reason, their processes are, automatically, killed and restarted but with different inputs. First, the MDO-SONDA interacts with missile datcom, obtaining the aerodynamic coefficients. Then, it writes the coefficients into the input file of ROSI, which also receives the mass and inertia properties of the rocket, i.e., the changes of mass, center of gravity, moment of inertia and product of inertia, computed by the MDO-SONDA due to spent stage separations, system releases and propellant consumption along the rocket flight.

One major benefit of the MDO-SONDA is to provide a user-friendly interface to insert input values and to check, graphically, outputs of both missile datcom and ROSI. It also provides the visualization of the input file of each executable code, which is automatically generated to make sure that there is not any apparent mistake.

Inputs

The MDO-SONDA inputs can be grouped in three parts. The first one consists of initial conditions, flight events and rocket definitions, which provide the entries to estimate the aerodynamic coefficients and to simulate the rocket trajectory. The second are the elements of the optimization problem: design objectives, variables and constraints. Lastly, the third ones are the optimization algorithm settings. With respect to

the first part, typical flight events are: stage ignition, burnout, spent stage separation, nose fairing ejection, and system release. Such events divide the trajectory calculation into phases, since they produce abrupt changes in the rocket configuration. For instance, the aerodynamic coefficients are given as a function of Mach and altitude for each change in rocket geometry, due to the separation of its parts, and jet plume, due to switching a motor on and off. Each phase is characterized by rocket definitions, which denote the phase configurations of the rocket. Thus, for each one, rocket definitions are: geometry of the body, propulsion data, and mass and inertia properties of each subsystem that still remains in the rocket during the flight. Using the Huygens-Steiner theorem, the MDO-SONDA computes the total mass and inertia properties of each phase configuration of the rocket.

Outputs

The MDO-SONDA provides an output interface for each executable code and for the optimization results. Using such interfaces, the user can save and analyze later the Pareto-optimal solutions by using the features of the output interface for missile datcom and ROSI in order to verify and validate the final results.

Optimization algorithm

Since it is expected that the objective functions have many local minima and maxima and unknown function's gradient, the appropriate methods are, traditionally, genetic algorithms and simulated annealing, according to the logic decision for choosing MDO, which was proposed by Rowell and Korte (2003). Considering the traditional approach, the MDO-SONDA is based on a multiobjective nongenerational genetic algorithm (Barbosa and Guimarães, 2012). The nongenerational approach is adequate for multiobjective issues, since it preserves individuals that are closer to the Pareto front (Valenzuela-Rendón and Uresti-Charre, 1997). The version of this genetic algorithm approach, which was used in this work, is based on the proposal of Borges and Barbosa (2000). The nongenerational algorithm starts generating and assessing the initial population, computing the fitness of each individual and ranking the population according to it. Then, predefined quantity of iterations is started, which will be satisfactory if all individuals become nondominated at the completion of the optimization. Each iteration consists of selecting two individuals, denoted by parents, generating their offspring that

includes two new subjects, computing their fitness and selecting the new individual with the best fitness, and testing the selected individual to decide on his/her inclusion into the population. Despite the denomination given to this genetic algorithm, nongenerational, each iteration denotes a generation, since a new individual can be introduced into the population. In the version used in this work, new individuals are accepted only if they are not bad than the worst individual in the population (Barbosa and Guimarães, 2012). Also, this work used a real operator that produces both diversification and intensification of the search for optimal solutions instead of the original binary operators, since the optimization problem of current interest is based on continuous objective functions.

The proposed real operator works on a normalized search space. Firstly, appropriate values are assigned to its parameters: coefficient of mutation (c), lower bound of mutation (k_{inf}), and upper bound of mutation (k_{sup}), where the first parameter is a real number and the last two are integers. Secondly, the operator visits each solution that were previously chosen to generate a descendant, running the following steps. Given a chosen solution, a variable (v) of it that is a design variable is randomly chosen to suffer mutation. Thirdly, an integer (k) is randomly generated between k_{inf} and k_{sup} , and a real value (p) is randomly generated between zero and one. Finally, the new value of v derives from the old one plus an increment (m), which is given by Eq. 2:

$$m = \begin{cases} -tv & \text{if } p = 0; \\ t(1 - v), & \text{otherwise} \end{cases} \quad (2)$$

where

$$t = c \cdot e^{-k/2} \quad (3)$$

In Eq. 3. when the coefficient of mutation c increases, the diversification of the search does the same. The more diversified, the more globalized the optimization is. However, it is important to establish a compromise between both diversification and intensification in order to avoid excessive evaluations of the objective function, if diversification weighs more than intensification, or premature convergence, otherwise.

How to proceed with the optimization

The optimization is a trial process. It consists of choosing the preliminary intervals for the design variables. The output interface for optimization results uses a method for analyzing multivariate data, which is called parallel coordinates. This

method consists of parallel lines, vertical and equally spaced, where each line corresponds to a design variable and the maximum and minimum values of each variable are usually scaled to the upper and lower boundaries on their respective lines (Grinstein *et al.*, 2001). Using this approach, one verifies, graphically, whether the promising region of the search space is reaching the lower and upper bounds or not. Then, if it does, it suggests that the bounds should be extended. Otherwise, it may suggest that the bounds should be more restrictive. Furthermore, the analyses of the optimization results may expose unfeasible conditions that were not considered before in the optimization problem. Thus, the optimization is also a learning process on the self-optimization problem.

CASE STUDY

This section presents the case study of the VS-40 by using the MDO-SONDA. Firstly, the elements of the optimization problem will be defined. Then, the settings of the multiobjective nongenerational genetic algorithm will be presented, and the solutions to improve the VS-40 fins will be commented. Finally, a mission analysis considering a hypothetical payload mass to microgravity experiment will be presented on the point of view of the trajectory discipline to evaluate the gain obtained with the improved fins in comparison with the VS-40 with its original fins taking into account the influence of wind and dispersion factors of the VS-40 on its flight.

Design problem statement

The design issue may be defined as follows. Given the original design of the VS-40 with a payload of 240 kg, and assuming that this mass is the minimum acceptable for this rocket, the goal is to find an improved design for its tail fins. To achieve such a goal, two design objectives were pursued: minimization of the drag force caused by the rocket fins; and maximization of the shortest interval between critical flight events, which are transonic speed, maximum dynamic pressure, minimum static margin, and pitch-roll crossing.

The second objective is commonly pursued to avoid subjecting the rocket to severe conditions that could induce an unstable behavior. The transonic speed refers to the range of Mach 0.8 to 1.4, in which severe instability can occur due to oscillating shock waves and large acoustic energy release. The maximum dynamic pressure is often related to the point of maximum aerodynamic load. Indeed, the fins have negligible influence on the instants of both the transonic speed and the maximum

dynamic pressure. Their responses are significantly related to the rocket propulsion. The static margin is the position of the center of pressure, where the aerodynamic forces act, minus the position of the center of gravity, both measured with respect to the nose tip as referential and positive in the direction of the rocket tail. If the static margin is negative, that is, the center of pressure is ahead of the center of gravity, the rocket is aerodynamically unstable. If it is positive but too small, it increases the rocket oscillations, which can affect the rocket performance. The pitch-roll crossing, that is, the crossing between the pitch and the roll rates, can lead to a physical phenomenon called roll resonance followed by the roll lock-in, where the roll rate deviates from its desired path (Cornelisse *et al.*, 1979). These two latter critical flight events are significantly affected by the fins of the rocket.

Before proceeding with the comments on the solutions to improve the VS-40 fins, an unobvious question was answered: when attempting to minimize the drag due to fins, does the second objective suffer as a result? It is also demonstrated that the MDO methodology can be used to investigate whether design objectives are competing or not, leading to a more comprehensive understanding of the system's trade-offs.

Figure 3 describes the design variables. The VS-40 is a body-tail rocket configuration with four identical tail fins, arranged in a cruciform geometry. Its fins have hexagonal airfoil geometry and two segments. In this case study, only the second segment was subjected to optimization (Fig. 3). Still, the variation of mass and inertia properties related to the shape change of the fins was neglected.

The intervals of shape variation of the fins are established in Table 1, which defines the continuous design search space for optimization.

Table 1. Bounds of the design variables.

Design variable	Nominal	Lower bound	Upper bound
1 (degrees)	0.6	0.42	0.6
2 (m)	0	0	2.4843
3 (m)	0.7095	0.7095	0.9095
4 (m)	1.2513	1	1.2513
5	0.348038	0.348038	0.417646
6	0.799168	0.719	0.959002
7 (m)	0.016783	0.011748	0.016783

The optimization was subjected to the following side constraints: roll rate ≤ 2.3 Hz, and static margin ≥ 1.4 calibers. Such constraints are necessary because excessive roll rate affects the structure, and too small static margin increases oscillations. Both situations can affect rocket performance.

Optimization settings and results

Table 2 presents the settings of the multiobjective nongenerational genetic algorithm used in MDO-SONDA. It also shows that the neighborhood radius and the graduation factor are parameters of the fitness function, which regulate the distribution of solutions along the Pareto front (Borges and Barbosa, 2000).

Despite the small number of design variables, this case study showed that computational cost could become an issue. A single simulation involving interactions between aerodynamics and trajectory calculations takes 12 seconds in a 3.0 GHz Dual Core. Since 1,200 evaluations of the objective function were required for seven design variables, the optimization took four hours.

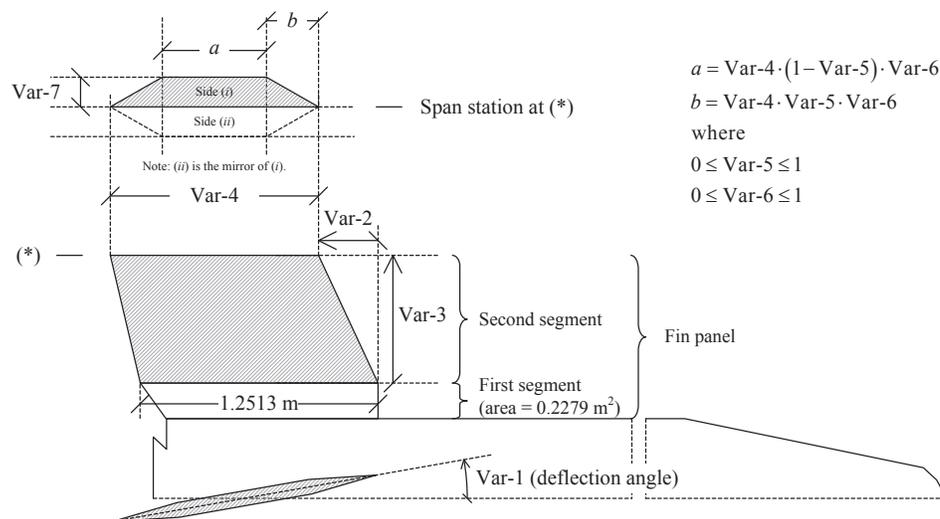


Figure 3. Design variables of the tail-fin airfoil and geometry.

Table 2. Optimization algorithm settings.

Parameter	Value
Size of the population	20
Number of generations	600
Neighborhood radius	2
Graduation factor	0.5
Coefficient of mutation	1.4
Lower bound of mutation	1
Upper bound of mutation	6
Float-point precision	0.001

We have found a Pareto front, demonstrating that the minimization of the drag due to fins and the maximization of the shortest interval between critical flight events are competing objectives (Fig. 4).

It seems that the fitness function, as proposed by Borges and Barbosa (2000), gave well-distributed points along the Pareto front (Fig. 4). However, despite the fact that population size was fixed at 20 (Table 2), Fig. 4 only presents a set of 11 points. Indeed, in some of these points, there is more than one solution with slight differences between them.

Optimization results seem to be coherent. The interval between the transonic speed and the maximum dynamic pressure events is 15 seconds, no matter what fins are used. The optimization could not lead to solutions that exceed such interval (Fig. 4). Also, the drag due to the rocket fins can be reduced up to 29% without increasing the chances of adverse effects that could lead to unstable behaviors (Fig. 4). There are some chances that adverse effects increase when two or more critical flight events occur at the same instant. Figure 4 shows

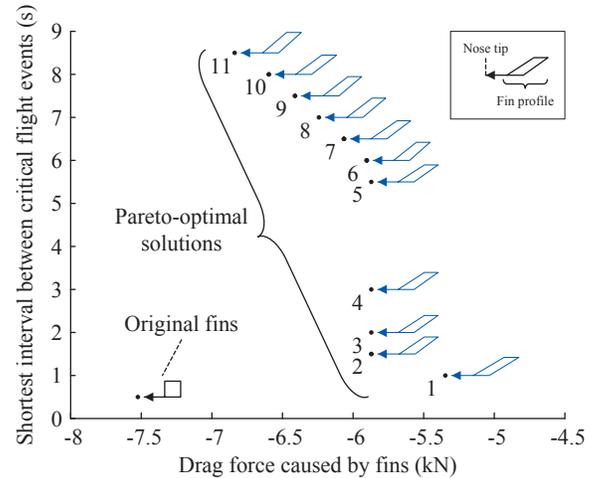


Figure 4. Optimization results.

on *x*-axis the total drag minus its value without computing the fins in the drag coefficient calculation, which is -40.24 kN. Thus, in terms of the total drag, the reduction was up to 5%.

Regarding the parallel coordinates graph, the promising area of the search space has reached the limits of almost the totality of the design variables (Fig. 5).

In Fig. 5, regarding the line of Var-7, which is related to the thickness of the fins, the results suggest that the lower bound has to be reduced. Certainly, the bounds have to be kept when they also want to avoid unfeasible solutions. Therefore, the lower bound of Var-7 is kept, assuming that its reduction can lead to structural issues.

Table 3 presents a Pareto-optimal solution associated with each point in Fig. 4. It is worth noting, based on Var-3 and Var-4 values in Table 3 and the chord at the base of the second segment of the fin panel and the area of the first one

Table 3. Dimensions of fins for the VS-40.

Solution*	Variable 1 (m)	Variable 2 (m)	Variable 3 (m)	Variable 4 (m)	a (m)	b (m)	Variable 7 (m)
Original	0.600	0.000	0.710	1.251	0.652	0.348	0.0168
1	0.587	2.429	0.793	1.167	0.584	0.382	0.0117
2	0.589	1.995	0.787	1.084	0.608	0.426	0.0118
3	0.550	1.995	0.787	1.084	0.597	0.418	0.0118
4	0.526	1.995	0.787	1.084	0.584	0.409	0.0118
5	0.427	1.995	0.787	1.084	0.577	0.409	0.0118
6	0.420	1.766	0.793	1.095	0.610	0.440	0.0117
7	0.420	1.995	0.812	1.095	0.626	0.423	0.0117
8	0.420	1.995	0.842	1.066	0.603	0.416	0.0118
9	0.421	1.995	0.862	1.089	0.622	0.421	0.0118
10	0.420	2.029	0.862	1.212	0.690	0.470	0.0117
11	0.422	1.855	0.905	1.196	0.684	0.461	0.0118

*solutions are ordered as in Fig. 4.

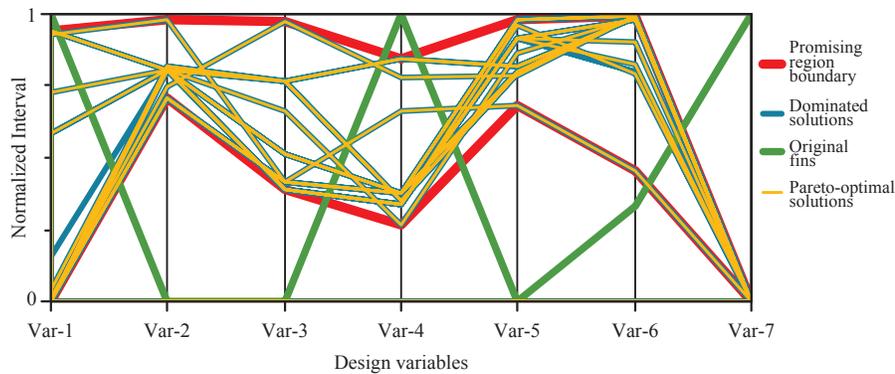


Figure 5. Visualization of the parallel coordinates.

showed in Fig. 3, the Pareto-optimal solutions have from 2.8 to 19.6% more surface than the original panel. Surface area often has more impact than geometry, increasing the drag, despite any attempts to reduce it by choosing an adequate geometry. However, the extended surface area of the Pareto-optimal solutions does not seem to cause any disadvantage in comparison with the original fins.

Figure 6 is evidence that the original fins are not adequate. The original fins of the VS-40 have rectangular panels (Fig. 1b). Among the panel geometries for fins, the rectangular is the one that provides more drag in supersonic speed, based on equal surface area and span between the geometries (Fleeman, 2006). Despite the reduced surface area of the original fins, it causes more drag than the Pareto-optimal solution number 11, which has the largest surface area.

Among the Pareto-optimal solutions, the drag increases as the surface area increases, demonstrating the steady influence of the surface area (Fig. 6). However, the solution number 1 is an outlier, since it causes less drag than solutions from 2 to 7 but it has an area slightly extended with similar geometry (Fig. 4). Solutions are ordered as in Fig. 4.

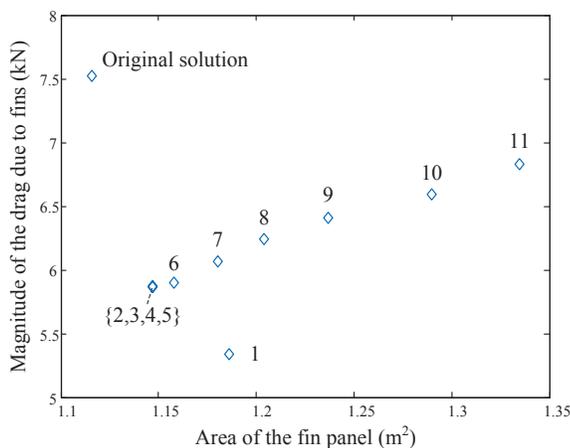


Figure 6. Drag due to fins *versus* fin panel area.

Despite the fact that solutions providing the shortest interval between critical flight events greater than two seconds are those safer than the solution number 1, for mission analysis, the improved fins were selected, since it is the Pareto-optimal solution that causes the largest reduction of the drag, increasing the rocket's performance.

Mission analysis

The proposed mission to be analyzed is characterized by a hypothetical payload of 240 kg, which is carried by the VS-40 to be exposed to microgravity environment. If one suppose the mission is scheduled for December, corresponding to the transition between the dry and rainy periods in CLA (Castro and Fisch, 2007), when wind surface reduces gradually with the occurrence of rain, the operation will be benefited. The goal is to evaluate what is the gain in the performance of the VS-40 with the improved fins in comparison with its original ones considering this hypothetical mission.

The maximum expected gain can be estimated without performing any optimization. The trajectory simulation without computing the fins in the drag coefficient calculation provides an expected gain of 2.9% (Fig. 7). Despite the small influence of the fins on the performance of the rocket in microgravity, as reflected by the small expected gain, it was seen that the conditions of a mission analysis can affect the gain due to improvement of the rocket fins.

Ignoring the influence of the wind and of dispersion factors of the VS-40 on its flight, a total drag reduction of 5%, using the improved fins, causes an elapsed flight time gain in microgravity of 1.6% (Fig. 7). However, since the VS-40 is an unguided rocket, wind effects and dispersion factors should be considered. The mission analysis consists of taking into account these factors in the evaluation of the VS-40 configurations, one with the improved fins and another

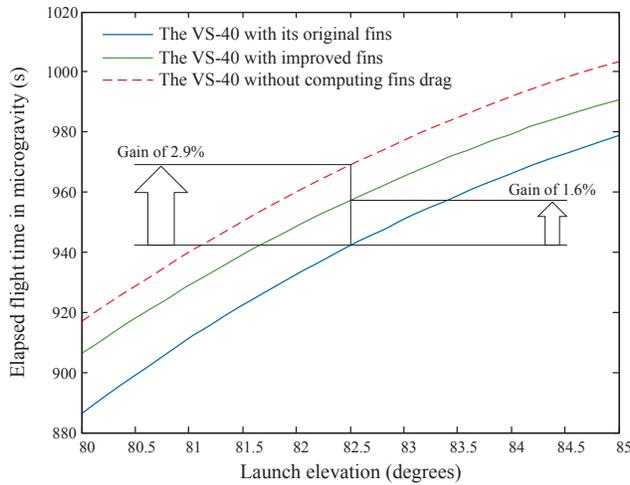


Figure 7. Elapsed flight time capability in microgravity environment varying with launch elevation. The upper elevation is 85°, according to Centro de Lançamento de Alcântara (2008).

with the original fins. The launch azimuth and elevation that provide the desirable probability to proceed briefly with the mission are firstly obtained by considering the wind effect. Then, fixing the adequate launch azimuth and elevation for each VS-40 configuration, the theoretical deviation of the elapsed time in microgravity is estimated by considering the dispersion factors of the rocket. Finally, the gain in the performance of the VS-40 with the improved fins is estimated based on the average value of the elapsed time in microgravity, in comparison with its original configuration.

A large percentage of the total wind influence on the rocket occurs very early in flight. During an operation in the Brazilian territory, to compensate for the wind effect, it is necessary to adjust the launch azimuth and elevation based on wind data, which are collected few moments before liftoff. Two types of wind sensing devices are provided, rawinsondes to high altitudes and anemometer measurements of wind surface profile. The procedure to make the launch azimuth and elevation adjustments for sounding rockets, still adopted by the Brazilian launch centers, is based on Hennigh (1964). It consists of determining, for a range of launch elevations, the wind weighting as a function of the altitude, and the splashdown displacements caused by a unit range- and cross-wind, respectively. Such displacements are determined by considering the wind up to an upper limit of the effective atmosphere. The range-wind azimuth is given in the direction of the rocket launch tower, while the crosswind is normal to it. Then, given a wind profile as input, the procedure consists of evaluating the ballistic wind, combining data provided by the wind sensing devices with

the wind weighting function, which had been previously calculated. The ballistic wind is hypothetical and constant in direction and magnitude from the ground level to a defined upper limit of the effective atmosphere. In practice, the upper limit of the effective atmosphere is roughly 25 km (Hennigh, 1964). Finally, considering the ballistic wind, the splashdown displacement caused by a unit wind, and the assumption that the response of the rocket is linear with the wind velocity, the launch azimuth and elevation are adjusted. However, due to stochastic behavior of the wind, dispersion factors of the rocket, structural issues, geographical constraints, and rocket assumption of the linear response to make the adjustments, the following constraints should be considered: $80^\circ \leq El_A \leq 86^\circ$, $-20^\circ \leq Az_A \leq 120^\circ$, $|El_C - El_R| \leq 4^\circ$, and $|Az_A - Az_R| \leq 35^\circ$, where El_A and Az_A are, respectively, the adjusted elevation and azimuth; and, El_R and Az_R are, respectively, the reference elevation and azimuth.

Using 50 samples of wind profiles collected at CLA in December 2008, obtained with sensors, we have estimated the probability of not violating such constraints for a range of launch azimuth and elevation values, given to one attempt of launch (Fig. 8).

Suppose the hypothetical mission cannot exceed two attempts of launch, given that the probability for one attempt (P) can be expressed by Eq. 4:

$$p = 1 - (1 - P_n)^{\sqrt[n]{n}} \tag{4}$$

where, P_n is the probability, between 0 and 1, for n attempts of launch.

In order to not exceed the limit of attempts, fixing P_n at 0.98, for instance, the probability of not violating constraints of launch azimuth and elevation can be at least 0.9 (90%). As the elapsed time in microgravity increases with the launch elevation (Fig. 7), let us select the maximum launch elevation for each VS-40 configuration associated with 90% of nonviolation of the constraints. Based on Fig. 8, the VS-40 with improved fins can be launched at 82°, and with the original fins, 81.5°. These are the maximum launch elevations. The launch azimuth can be fixed at 40° for both configurations.

The theoretical deviation of the elapsed time in microgravity is determined by using Monte Carlo’s method, which consists of varying the dispersion factors, and computing their results on the trajectory of the rocket, assuming a normal distribution on their variation interval, which is defined by their respective error. The aerodynamic coefficients are, for instance,

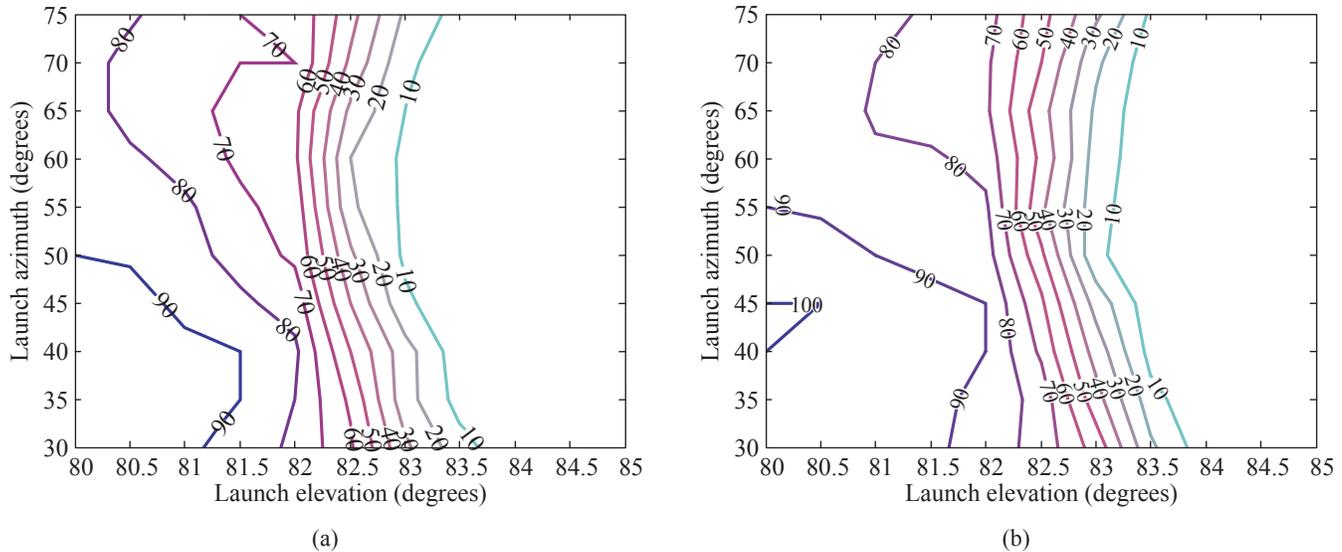


Figure 8. Probability of not violating constraints of launch azimuth and elevation adjustment to compensate for the wind effect (%), given to one attempt of launch. (a) VS-40 with its original fins; (b) VS-40 with the improved fins.

dispersion factors to be considered. Studies that evaluate the accuracy of the missile datcom compared to experimental wind tunnel data shows that the results for aerodynamic drag are predicted by missile datcom with an error, whose magnitude is less than 20% for a variety of rocket geometries (Sooy and Schmidt, 2005). At transonic speeds, where boundary layer shock interaction takes place, missile datcom does not have the capability to accurately represent such kind of interaction. Table 4 presents the dispersion factors that were assumed to calculate the deviation of the elapsed time in microgravity.

Table 4. Dispersion factors error for each rocket stage.

Dispersion factor	Error	
	First stage	Second stage
Launcher elevation error (degrees)	±0.5	–
Launcher azimuth error (degrees)	±3.0	–
Head and cross wind (m/s)	±2.0	–
Thrust variation (%)	±3.0	±3.0
Thrust misalignment in pitch and yaw (degrees)	±0.1	±0.1
Aerodynamic drag (%)	±20.0	±20.0
Weight variation (%)	±1.0	±1.0
Fin misalignment (degrees)	±0.01	±0.01
Ignition time variation (s)	–	±2.0

No predominant wind speed and direction have been considered in the calculation of the deviation of the elapsed time in microgravity. Table 5 presents the deviation of the elapsed time in microgravity.

Table 5. Average value and error of the elapsed time in microgravity.

Launch elevation (degrees)	Elapsed time in microgravity (s)	
	With original fins	With improved fins
81.5	922±138	939±134
82	932±138	949±129

Considering the maximum launch elevations, the elapsed time gain in microgravity provided by the improved fins can increase from 1.6 to 2.9% (Table 5). As previously discussed, the expected gain does not seem to justify any attempt of changing the fins of the VS-40. Besides, the expected error is approximately five times the gain in microgravity (Table 5). On the other hand, it was demonstrated that the factors associated with the mission analysis could affect the gain evaluation. It is expected that, by involving more subsystems and design disciplines in future works, significant improvements in the Brazilian sounding rockets can be demonstrated regarding different applications, besides their application in microgravity experiments.

FUTURE WORKS

In future works, at least four lines of development should be considered. First, new functionalities may be added to the MDO-SONDA. Interfaces might be created for graphical comparisons of the aerodynamic coefficients between phase configurations, 3D visualization of the rocket, and customized plots of the trajectory parameters. The user should be able to customize the optimization problem and to set the interaction

with a new high-fidelity executable code by using an interface instead of adding to or replacing a specific subroutine in MDO-SONDA. This latter should be able to recalculate the mass and inertia properties of the rocket considering the change of the shape that is being optimized. Data-mining methods might be included in the future to assist the user on searching for trade-offs, when the number of design variables and objectives are such that the traditional methods of data visualization are not enough to make them explicit. Also, the MDO-SONDA should be compared with other codes.

Second, more high-fidelity codes may be linked to MDO-SONDA, involving more design disciplines. For instance, teamwork involving experts in propulsion and structure might provide, respectively, specific codes to generate the thrust curve from the propellant variables and to estimate the structural resistance of the rocket against aerodynamic loads during the flight. Furthermore, an analysis can be performed to study the influence of the error of the high-fidelity codes on the design optimization.

Third, the optimization mechanisms may be more diversified and sophisticated. Memetic algorithms are the combination of two or more metaheuristics, cooperating or competing with each other, and surrogate models might improve the overall performance of the optimization by reducing the number of objective function evaluations. Parallel computing might be used together with such approaches for large-scale optimization problems. The search for appropriate parameter values related to the optimization mechanisms are an issue for future works.

Finally, with respect to the last line of development to be seen in future, two or more subsystems may be redesigned, simultaneously, to improve the rocket, for instance, two or more sets of fins, fins and nose faring, and so on. Sensitivity analysis can be executed to investigate the impact of any variations of the design variables on the its objectives. In addition, two or more missions with respect to the same rocket may be simultaneously considered at the same optimization process.

CONCLUSIONS

In this paper, a MDO application in the context of Brazilian sounding rockets was demonstrated. As case study, the shape optimization of fins of the VS-40 was presented, regarding its next launches at the Brazilian territory to perform microgravity experiments. This paper began by introducing the concepts of sounding rockets and the microgravity environment, which was followed by presenting facts about the VS-40, and explaining

why it should be revised. Before commenting the results of the optimization, the main aspects of the MDO-SONDA were depicted. It was found that the minimization of the drag due to fins and the maximization of the shortest interval between critical flight events are competing objectives, leading to a more comprehensive understanding of the VS-40 trade-offs. The drag due to the rocket fins could be reduced up to 29%, and with an interval of at least one second between critical flight events, in order to avoid adverse effects that could lead to unstable behaviors. However, in terms of the total drag, the reduction was up to 5%, causing an elapsed flight time gain in microgravity of 2.9% without ignoring the influence of the wind and the dispersion factors of the rocket. Despite the small gain, it was demonstrated that the factors associated with the mission analysis could affect the gain evaluation. Finally, four lines of development for future works were suggested: the addition of new functionalities to MDO-SONDA; the participation of more design disciplines, contributing with their high-fidelity codes; the improvement of the optimization mechanisms, adding sophisticated methods, such as surrogate models; and the simultaneous optimization of two or more subsystems of the rocket.

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