DESIGN UPGRADE AND VALIDATION OF A LAUNCHER VEHICLE ATTITUDE CONTROLLER COMBINING GENETIC AND LINEAR QUADRATIC OPTIMIZATION

Fausto O. Ramos, fausto@iae.cta.br
Waldemar C. Leite Filho, waldemar@iae.cta.br
Instituto de Aeronáutica e Espaço (IAE / CTA)
Space Systems Division (IAE-ASE)
12228-904 - São José dos Campos - São Paulo - Brazil

Abstract. *The design upgrade of a launcher vehicle attitude controller combining linear-quadratic optimization and genetic optimization is considered. In a previous work, it was demonstrated how a smoothing factor included in the cost function can avoid large variations of a genetically generated gain vector for a launcher vehicle attitude controller. There, an interval of the vehicle simulated flight was chosen in order to apply the proposed idea, which was shown attractive, compared to the conventional design. Now, that idea is extended to the entire flight and verified through hardware-in-the-loop simulations, also considering non-ideal scenarios related to engine configurations ('weak' and 'strong' engines), external disturbances and bending tolerances.*

Keywords: *launcher vehicle, attitude controller, genetic algorithm, linear-quadratic design, optimization.*

1. INTRODUCTION

The VLS-1 (acronym, in Portuguese, for Satellite Launcher Vehicle) project was first mentioned in 1979, enclosed in the Complete Brazilian Space Mission (Portuguese acronym MECB), and its development started in 1989. Three flight models were built since then; two of them were launched (V01 in 1997 and V02 in 1999), but failures prevented full mission accomplishment. An accident with casualties occurred with the last model still on the launch pad, and led to an extensive revision of the project, with the cooperation of a Russian institution. Two technological models (XVT-01 and XVT-02, based on the VLS-1 conception) are expected to be developed and launched from a new launch pad in two years.

For the real flights of the models V01 and V02, the attitude controller performance was acceptable. However, further efforts are currently being carried to reduce the amplitude of the actuation signal driving the movable nozzle actuators, to minimize the effects of a non-linear phenomenon known as limit-cycle, also associated with the actuators and to lessen the influence of the bending modes on the launcher stability. Furthermore, the design stage performance indexes and robustness margins are supposed to be further improved through balanced adjustments.

The conventional (current) design of the VLS-1 attitude controller relies on the linear-quadratic technique, where a given instant of the flight is chosen when the aerodynamic load is maximal; after applying the Riccati equation on the state space description of the control system simplified model, the resultant closed loop poles are repeated for the remaining instants of the flight. Thus, the only choice of this procedure is to select convenient **Q** and R weighting values used in the Riccati equation, such that the associated performance indexes agree with the system specifications.

The procedure above was stated in the early 1990s, when the **Q** and R weighting values had been chosen by hand, in a 'trial-and-improvement' manner, till a best combination was found (best in the sense of the indexes obtained mainly of the simplified model); these values are still in use. However, it is possible today, once that personal computing and genetic algorithms are more developed and applied, to conduct an automated search directly in the detailed model, and even not only at a particular instant of time, but for all flight, as it will be shown here.

Section 2 states the launcher vehicle control system, summarizing the conventional design method. Section 3 presents the genetic algorithm and its cost function, which is combined with the conventional design in section 4. Section 5 presents the results provided by hardware-in-the-loop simulations of the combined design, for nominal and particular scenarios according engine configurations, external disturbances and bending tolerances; these results are further compared with those of the conventional design.

2. THE LAUNCHER ATTITUDE CONTROL SYSTEM (LACS).

2.1 System overview.

The VLS-1 vehicle has the following main characteristics (approximated values):

- **Physical.** Mass = 50 ton, height = 19m, 4 stages (solid propellant), 1^{st} stage composed of 4 boosters.
- **Mission.** Circular orbit insertion capability: (i) 100-380 [kg], equatorial orbit (200-1200 [km]), and (ii) 75-275 [kg], polar orbit (200-1000 [km]).

More details can be found in Leite Filho and Carrijo (1999).

2.2 Conventional LACS design procedure and validation.

The conventional LACS design procedure associates gain scheduling with a linear quadratic optimization of the control effort, attitude angle and its derivative, and angle error integral, producing a proportional-integral plus velocity feedback controller. The conventional design is given below, according Ramos and Leite Filho (2003) and Ramos et al. (2005):

- A particular instant of the vehicle trajectory simulation is searched when the aerodynamic load is maximal.
- The linear quadratic optimization, based on a simplified version of the control system (2^{nd} order plant plus controller), calculated at that instant, produces a closed loop transfer function, from which the poles are identified.
- The controller gains for each of the remaining instants are calculated based on the respective closed loop transfer functions, maintaining the *frozen* poles identified in the last step.

It is important to observe that, despite the linear quadratic technique being employed in the design, only a particular instant is optimized. The remaining ones just mirror the poles of the original closed loop transfer function, but are not optimized. Therefore, the intent of the genetic design proposed in this work is to optimize the controller for the entire flight, and, at the same time, approximate the gain vector history to a smooth curve.

For the LACS validation, the specifications to be met are mainly related to robustness and performance, regarding a linear detailed system composed of a 3^{rd} order plant, 2 bending modes, actuator, notch filter (for rejection of the 1^{st} bending mode) and controller. Scenarios are defined where engine configuration, bending mode frequency tolerances and synthetic wind profiles are also considered. Additionally, a non-linear digital simulation is executed in order to verify stability under parameter variation. The final step consists in the hardware-in-the-loop simulation, described by Leite Filho and Carrijo (1997).

3. THE GENETIC ALGORITHM.

The procedure for the genetic based design is shown in the figure 1. There, one assumes a system with time variant parameters; thus, a new model is defined for each *time*, upon which the controller gains are calculated for the n-element population (binary representation of each individual), modified through reproduction, cross over and mutation processes (figure 2). Then, the controller candidates are rated, based on certain indexes to be given next, where the best rated one is selected to the elitism process.

The cost function considers the well known indexes in the control engineering community: rise time (t_r), settling time (t_s), overshoot size (M_p), and gain and phase margins (m_g and m_p). Furthermore, a smoothing factor (S_f) is also included, which weights the relative magnitude of the gain vectors, according to the equation 1:

$$S_f = \sqrt{\frac{\sum_i [K_i(k) - K_i(k-1)]^2}{\sum_i [K_i(k-1)]^2}} \tag{1}$$

where $\mathbf{K}(k) = [K_1(k)\ K_2(k)\ ...\ K_n(k)]$, $i \leq n$ and k is the discrete design time.

The smoothing factor is necessary because the genetic way to produce the gain vectors does not address directly the relative variation of these vectors for consecutive design times, which is an important issue as shown by Clement et al. (2005); in this case, linear interpolation is permitted if the gains are sufficiently closer from each other.

The mapping from the indexes to the cost values is assigned as shown in figure 3. These unity values are further scaled to give the final rating points. Table 1 presents the parameters indicated in the figure 3 for each index.

Table 1. Parameter values of the cost function indexes (N. A. = not applied).

Index	I_0	I_1	I_2	I_3	I_4
t_r	`tr_inf`	`tr_min`	`tr_opt`	`tr_max`	`tr_sup`
t_s	`tr_min`	`tr_opt`	`ts_opt`	`ts_max`	`ts_sup`
M_p	N. A.	N. A.	0	`mp_max`	`mp_sup`
m_g	`mg_inf`	`mg_min`	`mg_opt`	N. A.	N. A.
m_p	`mp_inf`	`mp_min`	`mp_opt`	`mp_max`	`mp_sup`
S_f	N. A.	N. A.	0	`sf_max`	`sf_sup`

```
procedure gen_alg()
 Elite = Elite_init
 for time = initial_time:end_time
  NewModel = model(parameter(time))
  Population = {}
  for generation=1:max_number_gener
   Data = {Population,Elite}
   Population = evolute(Data)
   Data = {Population,NewModel}
   Rating = evaluate(Data)
   Elite = Population(max(Rating))
   if Rating_Steady_Value, break
  end generation
  Evolution(time) = Elite
 end time
 return Evolution
end gen_alg
```

Figure 1. The pseudocode of the main procedure *gen_alg*.

```
procedure evolute(Data)
 if isempty(Population)
  Population = randomize()
  return Population
 end
 Population = reproduce(Population)
 Population = crossover(Population)
 Population = mutate(Population)
 Population = elitism(Population,Elite)
 return Population
end evolute
```

```
procedure evaluate(Data)
 for element = 1:size(Population)
  Individual = Population(element)
  Gains = lqdesign(Individual,NewModel)
  Output = simulate(Gains,NewModel)
  Performance = analyse(Output)
  Data = {Performance, Stability, Gains}
  Score(element) = cost(Data)
 end element
 return Score
end evaluate
```

Figure 2. The pseudocode of the procedures *evolute* and *evaluate*.

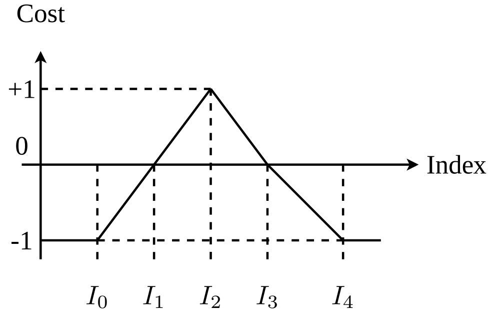

Figure 3. Mapping from constraints and indexes to cost values.

4. COMBINED DESIGN OF THE LACS.

4.1 Statements.

This section presents a comparison of: (i) two combined LACS designs, including or not the gain vector smoothing factor in the genetic algorithm cost function and (ii) the combined LACS design with smoothing factor given earlier and the conventional one (see section 2). The following conditions apply:

- Genetic algorithm characterization: 8 bit representation of each individual, 10 individuals per generation and maximal mutation rate of 5%.
- Performance indexes and robustness margins (see table 1): `tr_inf` = 0.5 [s], `tr_min` = 0.6 [s], `tr_opt` = 0.65 [s], `tr_max` = 0.8 [s], `tr_sup` = 1.0 [s], `ts_opt` = 5.0 [s], `ts_max` = 8.0 [s], `ts_sup` = 10.0 [s], `Mp_max` = 30 [%], `Mp_sup` = 35 [%], `mg_inf` = 6 [dB], `mg_min` = 9 [dB], `mg_opt` = 12 [dB], `mp_inf` = 15 [^{o}], `mp_min` = 30 [^{o}], `mp_opt` = 60 [^{o}], `mp_max` = 90 [^{o}] and `mp_sup` = 120 [^{o}].

The index-to-cost mapping of S_f (C_{sf}) is redefined as shown in equation 2, where `sf_max` = 0.5, S_{sf} is the cost-to-rating scaling factor and P_{max} is the maximal rating which can be obtained with the cost function. The new mapping imposes higher penalties to the individuals outside a given region of smoothness, avoiding large discontinuities of the gain vector due to the variation of the aerodynamic coefficients, used for the linear-quadratic design. **Note:** the individuals are gain vectors, each one composed of proportional, integral and velocity feedback gains (K_p, K_i and K_d respectively).

$$C_{sf} = 1 - K_{sf}\left[1 - e^{\left(\frac{-S_f}{S_{f,max}}\right)}\right], K_{sf} = \frac{P_{max}}{S_{sf}} \quad (2)$$

The time range considered for the trajectory simulation is full, from 1^{st} stage ignition to 3^{rd} stage burnout, thus extending the work of Ramos and Leite Filho (2007). However, there are certain regions of the trajectory (around lift-off and engine burnout) which demand special treatment. For example, during the lift-off when the vehicle is close to the launch pad and hence a collision may occur, the integral action of the controller should be reduced or even disabled. Therefore, after the combined optimization these regions are modified in order to comply with the imposed restrictions.

Other details of the genetic optimization are:

1. Intervals optimized: from maximal dynamic pressure to (a) 2^{nd} stage burnout and (b) 1^{st} stage ignition; few seconds before 3^{rd} stage burnout to (c) 3^{rd} stage burnout and (d) 3^{rd} stage ignition.
2. The first point of each interval is found with three times more individuals, to assure a better elite, from which the other ones will follow.

4.2 Evaluation of the combined design.

Observing figure 4, it is evident the contribution of the S_f factor to the controller optimization. The combined design presents a gain vector profile even smoother than the conventional design (figure 5). Moreover, it can be noticed that lower gain values are produced; this is an attractive feature for fault tolerant systems, as concluded by Ramos and Leite Filho (2001). (It is important to note the fast variations of the gain vector during lift-off and engine burnout; as was said before, these are regions dealt in a particular manner.)

Figures 6 and 7 presents the comparisons of the performance indexes and the stability margins between the combined LACS design with the smoothing factor and the conventional one. The genetic optimization improved the rise time (since a lower bound is required in order to reduce bending excitation), although the overshoot has increased, but not excessively. For the robustness issue, the gain margin is much higher during the most part of the flight, at the expense of subtracting few degrees of the phase margin.

The most notable result comes from the evaluation of the control signal; as shown in the figure 8 (obtained from a non-linear digital simulation), the linear quadratic optimization was fully achieved by the combined LACS design, since the maximal control effort was considerably smaller.

5. HARDWARE-IN-THE-LOOP SIMULATIONS.

This section presents and evaluates the results of the Hardware-in-the-loop (HWIL) simulations, for the nominal case and scenarios. Most of the simulations were executed as phase B ones (see Leite Filho and Carrijo (1997)), plus two phase D simulations (with real inertial sensors instead of just models), accounting for the nominal cases of conventional and combined LACS designs.

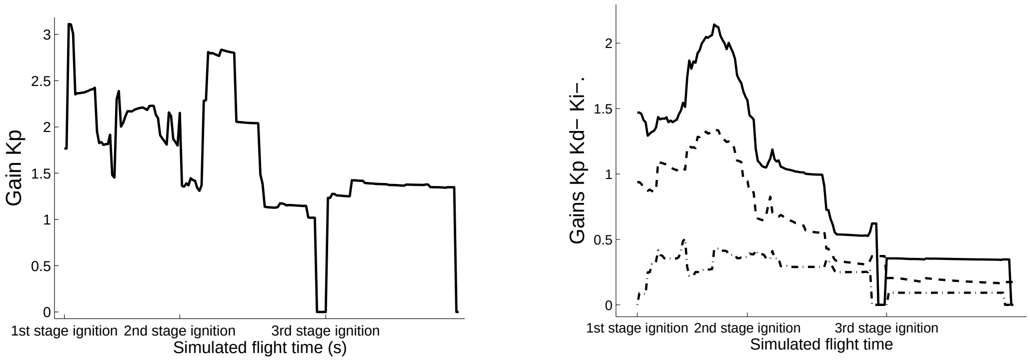

Figure 4. Controller gains obtained by the combined design without (left, proportional gain only) and with a smoothing factor S_f in the cost function.

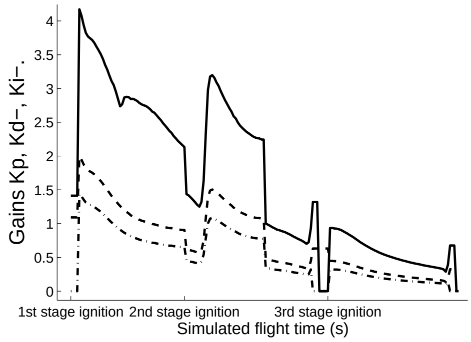

Figure 5. Controller gains obtained by the conventional design.

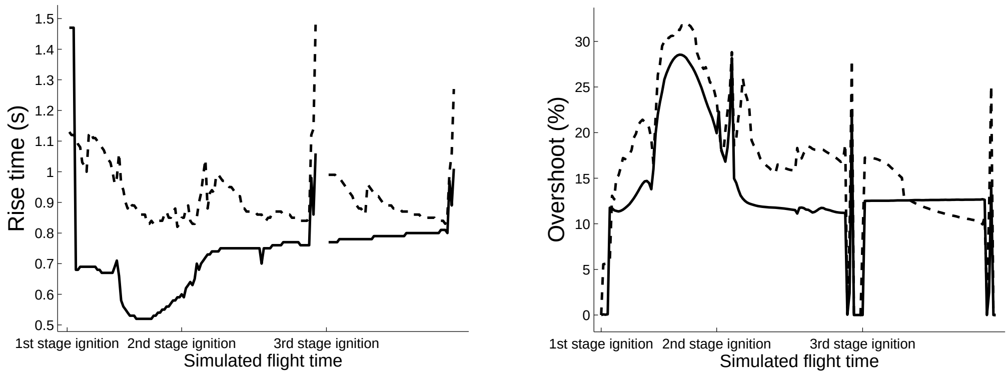

Figure 6. Rise time and overshoot: a comparison between the conventional and combined (-) designs.

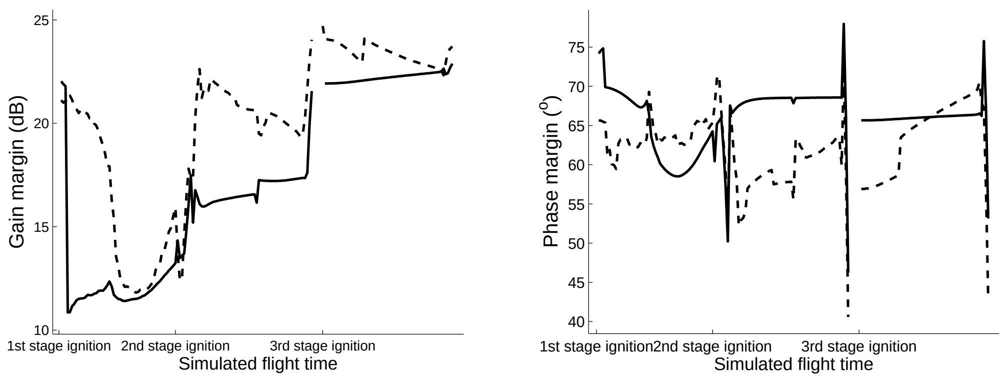

Figure 7. Gain and phase margins: a comparison between the conventional and combined (-) designs.

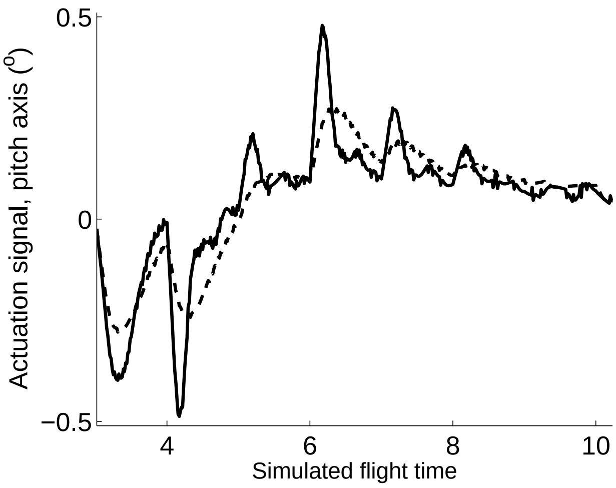

Figure 8. Maximal control effort (pitch axis): a comparison between the conventional and combined (-) designs (obtained from a non-linear digital simulation).

5.1 Scenarios for HWIL simulations, phase B.

The following scenarios were defined for the phase B HWIL simulations:

1. (Nominal) Nominal case for thrust force and bending modes. No external disturbance. Guidance disabled.
2. (Engine+,Engine-,EngUn) Engines: all strong, all weak, unbalanced. Nominal case for bending modes. No external disturbance. Guidance disabled.
3. (Bend+,Bend-) Bending modes: bending frequencies variation of +15% and -5%. Nominal case for thrust force. No external disturbance. Guidance disabled.
4. (Wind) External disturbance: wind synthetic profile. Guidance disabled. Nominal case for thrust force and bending modes.
5. (Guidance) Guidance enabled. External disturbance: wind synthetic profile. Nominal case for thrust force and bending modes.

The indexes used to compare both LACS designs (combined and conventional) are:

1. The integral of the squared control signal (ISCS).
2. The maximal amplitude of the 1^{st} and 2^{nd} bending modes (BM1,BM2), according to the Fast Fourier Transform of the pitch axis angular velocity. **Note:** BM2 is negligible during the 3^{rd} stage flight phase.
3. The maximal amplitude associated to the limit-cycle (LCyc) due to the actuator non-linearities, according to the Fast Fourier Transform of the pitch axis angular velocity.

Tables 2, 3 and 4 summarize the results for each flight phase. Regarding the ISCS index, small regions around lift-off and engine ignition and burnout were not taken into account. LCyc, BM1 and BM2 indexes were measured during the maximal dynamic pressure (1^{st} stage) and near engine burnout (2^{nd} and 3^{rd} stages). **Note:** for the 1^{st} stage, only the results of boosters 1A and 1B are presented, once they are representative of the other two. The main comments related to the simulations are:

1. The combined design presents better or equivalent results according ISCS index; the conventional design is superior only for Engine+ and Wind scenarios of the 1^{st} stage phase.
2. The results associated with the LCyc index are favourable to the combined design in the 1^{st} and 2^{nd} stage phases and favourable to the conventional design in the 3^{rd} stage phase, considering LCyc amplitudes and frequencies (for both characteristics, smaller values mean better evaluation).
3. The first bending mode is a problem for both designs during the 2^{nd} stage phase. For the EngUn and Bend– scenarios, the combined design is inferior; however, for scenarios Engine– and Wind, the conventional design performed even worse, and unsatisfactorily (yet stable) for the Bend+ scenario.

Table 2. Results of the HWIL simulations, phase B, 1^{st} stage.

Scenario	LACS Conventional Design				LACS Combined Design			
	ISCS (1A)	ISCS (1B)	LCyc	BM1, BM2	ISCS (1A)	ISCS (1B)	LCyc	BM1, BM2
Nominal	6.3	11.6	0.4@1.2Hz	3.6,0.3	5.6	11.4	1.2@1.4Hz	0.6,0.1
Engine+	5.2	14.3	0.9@1.1Hz	0.9,0.4	5.4	14.6	0.5@1.0Hz	1.2,0.8
Engine–	5.6	9.3	1.0@1.0Hz	1.6,0.4	5.2	9.1	0.6@1.2Hz	1.8,0.2
EngUn	5.8	18.3	1.0@1.1Hz	0.9,0.4	5.8	18.4	0.3@1.5Hz	0.8,0.1
Bend+	5.1	12.0	1.6@1.1Hz	12.5,0.1	5.1	11.5	0.3@1.5Hz	18.5,0.6
Bend–	5.3	11.7	0.6@1.1Hz	0.4,0.3	5.1	11.6	0.4@1.5Hz	0.2,0.3
Wind	30.1	23.4	1.9@1.2Hz	0.6,0.3	35.9	25.6	1.0@1.5Hz	1.0,0.1

Table 3. Results of the HWIL simulations, phase B, 2^{nd} stage.

Scenario	LACS Conventional Design				LACS Combined Design			
	ISCS (Pitch)	ISCS (Yaw)	LCyc	BM1, BM2	ISCS (Pitch)	ISCS (Yaw)	LCyc	BM1, BM2
Nominal	18.8	66.0	1.9@1.1Hz	272.0,0.8	16.9	66.3	0.9@1.4Hz	126.0,0.4
Engine+	16.3	67.5	1.9@1.4Hz	92.6,0.2	16.8	66.4	0.2@1.6Hz	0.4,0.0
Engine–	19.8	71.5	1.7@0.8Hz	930.0,0.5	19.1	71.1	2.2@0.9Hz	30.7,1.4
EngUn	17.9	67.2	0.9@1.2Hz	188.0,0.6	17.4	64.4	0.7@0.9Hz	360.0,0.7
Bend+	33.9	69.2	1.3@1.0Hz	14449.0,0.4	16.7	65.7	2.9@0.9Hz	143.5,1.0
Bend–	17.5	66.5	1.5@1.1Hz	182.6,0.3	17.0	65.4	2.0@0.7Hz	303.0,0.5
Wind	17.9	68.1	3.0@1.4Hz	1420.5,0.9	17.1	66.9	2.6@0.7Hz	5.5,0.4

Table 4. Results of the HWIL simulations, phase B, 3^{rd} stage.

Scenario	LACS Conventional Design				LACS Combined Design			
	ISCS (Pitch)	ISCS (Yaw)	LCyc	BM1	ISCS (Pitch)	ISCS (Yaw)	LCyc	BM1
Nominal	15.5	74.1	22.4@1.0Hz	0.2	15.2	68.9	4.9@1.1Hz	0.2
Engine+	14.9	70.4	0.3@1.1Hz	0.0	14.8	69.7	17.8@1.1Hz	0.2
Engine–	16.2	69.9	7.7@1.1Hz	0.1	15.9	69.9	12.4@1.1Hz	0.3
EngUn	16.0	71.5	7.8@0.7Hz	0.2	15.6	69.0	8.1@0.9Hz	0.1
Bend+	14.6	71.1	14.0@1.2Hz	0.0	14.2	67.7	10.4@0.9Hz	0.0
Bend–	14.4	70.5	7.1@0.7Hz	0.2	14.5	68.2	8.7@1.1Hz	0.3
Guidance	15.3	69.2	1.3@1.1Hz	2.6	15.9	68.0	2.5@1.4Hz	1.0

5.2 HWIL simulations, phase D (inertial sensors included).

Phase D and phase B simulation results agreed, according the indexes given. Besides, the actuation signals (figure 9) confirmed the same behaviour seen in the non-linear digital simulation (figure 8).

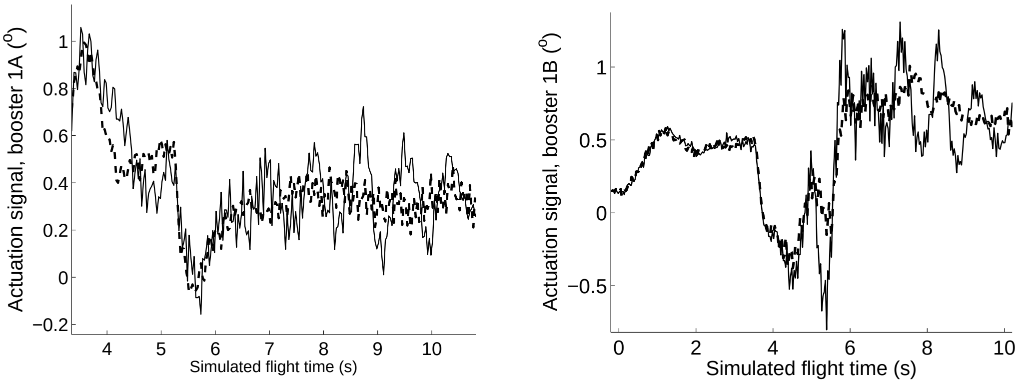

Figure 9. Control effort (boosters A and B of the 1^{st} stage): a comparison between the conventional and combined (-) designs (obtained from hardware-in-the-loop phase D simulations, nominal scenario).

6. CONCLUSIONS.

As observed by Ramos and Leite Filho (2007), the conventional VLS-1 attitude controller design does not fully optimize a given state vector to the entire time of flight, but only at a particular instant; thus, a motivation was found for combining it with a genetic-based approach, in order to linear-quadratically calculate the gain vectors for all and each flight instant. However, for limiting the variation of the gain vector (necessary due to stability matters), a smoothing factor is added into the cost function composed normally of performance and robustness indexes.

The combination of the genetic algorithm with the conventional LACS design is satisfactory, and the smoothness degree of the proposed solution is superior. Globally, the number of favourable performance and robustness indexes and dynamic properties of the combined design is superior compared with the conventional one. The linear quadratic optimization is extended to the full launcher flight and the maximal control effort is reduced, as observed in all non-linear simulations.

The validation of the new design is obtained through hardware-in-the-loop simulations, where it exhibits better characteristics regarding ISCS index, and even performs normally for a Bend+ scenario, where the conventional design is unsatisfactory (yet stable). Therefore, examining the indexes collected, and also the gain values produced (recalling their influence when sensor faults are present), this proposal is found to be not only promising, but candidate to replace the conventional LACS design.

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