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Tuning Techniques Evaluation for Satellite Launch Vehicle Attitude Controllers

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ABSTRACT: This communication presents a comparative analysis of tuning techniques for satellite launch vehicle attitude controllers. The investigated tuning techniques consist in the minimization of specific performance indexes, namely the Integral Absolute Error (IAE) index, the Integral of Time Multiplied Absolute Error (ITAE) index, the Integral Squared Error (ISE) index, and the Integral of Time Multiplied Squared Error (ITSE) index, being hence, termed optimal. By defining adequate figures of merit, relevant for evaluating the overall performance of satellite launch vehicles, and also taking into account requirements related to the physical limitations of the latter, the performance of attitude controllers tuned by the investigated techniques is compared to the one tuned by the methodology currently employed in the Brazilian Satellite Launch Vehicle (VLS), namely, the Linear Quadratic (LQ) methodology. Through simulation results, it is demonstrated that, despite sparse benefits produced by the alternative tuning techniques, in particular ITAE and ISE, the LQ methodology remains globally superior.

KEYWORDS: Spacecraft launching, Attitude control, Tuning, Linear quadratic Gaussian control, Performance indexes, Optimization.

INTRODUCTION

The Brazilian Satellite Launch Vehicle (VLS) is a launcher endowed with 4 independent propulsive stages, approximately 50 tons of weight and 19 meters height, whose main purpose is to insert payloads (up to 350 kg) in circular orbits, which can range from 250 km to 1000 km of altitude (Ramos *et al.* 2003). In order to enable effective fulfillment of its mission, the VLS control system is designed with three attitude control loops, one for each of its first three stages (Leite Filho 1999); two guidance/pointing loops, in the third and fourth stages, respectively (Melo *et al.* 2012); and a navigation algorithm, which operates during the whole vehicle flight, determining its inertial attitude, position and velocity (Oliveira *et al.* 2012).

In general, the aforementioned attitude control system can be analyzed and designed as being composed of three (ideally) uncoupled controllers, each one acting on a specific maneuvering plane of the vehicle, namely, the roll, pitch and yaw planes (Campos 2005). The control strategy currently implemented for each of the VLS attitude controllers is based on the frozen pole technique (Ogata 1997), and consists (with the exception of the roll plane controller) in a proportional-integral-derivative (PID) controller with derivative feedback structure (Silva 2014), tuned by linear quadratic (LQ) methodology (Ramos *et al.* 2003).

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The main objective of this communication is to investigate alternative tuning techniques for the aforementioned VLS PID attitude controllers. These techniques are based on the optimization of performance indexes other than the LQ, namely the Integral Absolute Error (IAE) index, the Integral of Time Multiplied Absolute Error (ITAE) index, the Integral Squared Error (ISE) index, and the Integral of Time Multiplied Squared Error (ITSE) index, which will be duly defined throughout this paper.

Based on intrinsic design requirements, related to the physical limitations of the vehicle, and on relevant figures of merit describing the overall performance of the system, a comparative analysis of the investigated techniques is presented. As main contribution of this communication, we demonstrate that, despite sparse benefits produced by the alternative tuning techniques, in particular ITAE and ISE, the LQ methodology remains the most suitable tuning technique for the purpose of the VLS attitude controllers design.

ATTITUDE CONTROLLER DESIGN

The design of an attitude control system for satellite launch vehicles translates into a highly challenging, nonlinear, time-varying, and flexible structure control problem (Silva and Leite Filho 2013). The methodology usually employed to solve this problem consists in linearizing the vehicle dynamics around its nominal operating condition, also considering that, within short time intervals, the vehicle parameters can be considered almost constant. In fact, these parameters vary very slowly, except during the lift-off and the transonic phase (Wie 2008; Greensite 1970). This methodology allows us to use classic control techniques to analyze the dynamic behavior of the vehicle, in all flight instants.

From the attitude control point of view, both the rigid body and bending modes are relevant. A common strategy is to design a rigid-body controller with comfortable stability margins, and then to apply a notch filtering to tackle the vehicle bending (Greensite 1970). A further step is to verify if this two-step design achieves good performance without major degradation of the stability margins. In this paper, it is studied the rigid body controller design.

The vehicle rigid body model, for each maneuvering plane, can be represented by the following third order transfer function (Eq. 1) (Silva 2014),

$$G(s) = \frac{\theta(s)}{\beta(s)} = \frac{-\mu_\beta s + \dfrac{\mu_\alpha z_\beta - \mu_\beta z_\alpha}{u}}{s^3 + \left(\mu_q + \dfrac{z_\alpha}{u}\right)s^2 + \left(\dfrac{\mu_q z_\alpha}{u} - \mu_\alpha\right)s + \dfrac{\mu_\alpha g}{u}} \quad (1)$$

where θ represents the angle to be controlled; β is the mobile nozzle deflection; u is the vehicle longitudinal velocity; z_α and z_β are linear acceleration coefficients (per unit of angle), related to the aerodynamic and control forces, respectively; and μ_α, μ_β and μ_q are angular acceleration coefficients (per unit of angle).

Assuming, in practice, that the vehicle longitudinal velocity u assumes large values, and that the term μ_q can be neglected (Brito *et al.* 2005), a simplified transfer function $G_S(s)$ for the launcher rigid body dynamics can be obtained (Eq. 2),

$$G_S(s) = \frac{\theta(s)}{\beta(s)} = \frac{-\mu_\beta}{s^2 - \mu_\alpha} \quad (2)$$

or, in the state space form (Eq. 3),

$$\begin{bmatrix} \acute{\theta}(t) \\ \acute{\theta}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \mu_\alpha & 0 \end{bmatrix} \begin{bmatrix} \theta(t) \\ \acute{\theta}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -\mu_\beta \end{bmatrix} \beta(t) \quad (3)$$

Since, in general, μ_α assumes positive values throughout the whole vehicle flight (Ramos *et al.* 2003), it is straightforward to conclude, from Eq. 2, that the system is unstable in open loop.

As already mentioned in the preceding Section, the structure of the Brazilian VLS attitude control system (for the pitch and yaw maneuvering plans) is of the PID type, with derivative feedback. This structure is shown in Fig. 1.

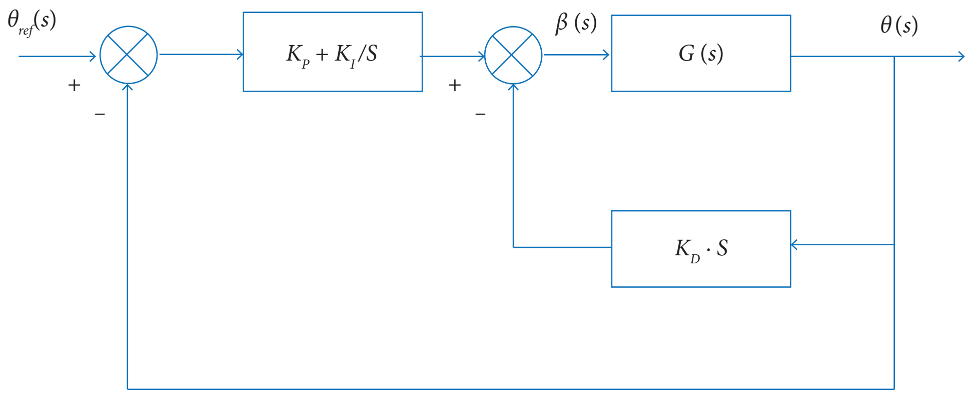

Figure 1. Block diagram of the Brazilian VLS attitude control system.

The structure of Fig. 1 is traditionally adopted in preliminary stages of the control system design, in addition to the simplified transfer function of the vehicle rigid body dynamics, given in Eq. 2, also neglecting the existence of eventual actuators and sensors dynamics. According to Wie (2008), the consideration of the actuator dynamics greatly depends on the actuator fabrication technology, which produces a bandwidth that may or may not be considered for the purposes of the design. In the case of the Brazilian VLS, its bandwidth is four times larger than the rigid body, and hence, it may be adequately neglected (Silva *et al.* 2013). The eventual influence of the actuator on the stability margins is previously taken into account during the rigid-body controller design.

Thus, the closed-loop transfer function $G_{CL}(s)$ of the system, considering the simplified launcher rigid body dynamics, is given by (Eq. 4),

$$G_{CL}(s) = \frac{\theta(s)}{\theta_{ref}(s)} = \frac{-\mu_\beta K_P s - \mu_\beta K_I}{s^3 + \mu_\beta K_D s^2 + (\mu_\alpha + \mu_\beta K_P)s + \mu_\beta K_I} \tag{4}$$

where θ_{ref} is the setpoint for the controlled angle; and K_P, K_I and K_D are the proportional, integral and derivative feedback gains, respectively.

Equation 4 can also be expressed in the state space form. Since the PID control action has the form (Eq. 5),

$$\beta(t) = -K_D\acute{\theta}(t) + K_P[\theta_{ref}(t) - \theta(t)] + K_I \int [\theta_{ref}(t) - \theta(t)]dt \tag{5}$$

it is necessary, in this case, to include a new state variable τ, to represent the integral term of the error throughout the process (Rossi 2003), i.e (Eq. 6),

$$\tau(t) = \int [\theta_{ref}(t) - \theta(t)]dt \tag{6}$$

Therefore, in state space form, we have (Eq. 7),

$$\begin{bmatrix} \acute{\theta}(t) \\ \acute{\theta}(t) \\ \acute{\tau}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \mu_\alpha & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta(t) \\ \acute{\theta}(t) \\ \tau(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -\mu_\beta \\ 0 \end{bmatrix} \beta(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \theta_{ref}(t) \tag{7}$$

with (Eq. 8),

$$\beta(t) = \begin{bmatrix} -K_P & -K_D & K_I \end{bmatrix} \begin{bmatrix} \theta(t) \\ \acute{\theta}(t) \\ \tau(t) \end{bmatrix} + K_P \theta_{ref}(t) \tag{8}$$

In the subsequent Section, suitable tuning techniques for the determination of the attitude controller feedback gains are presented and analyzed.

TUNING TECHNIQUES EVALUATION

Although μ_α and μ_β vary slowly, their values can assume a considerably wide range during an entire phase of flight. Hence, the controller performance would be dependent of the flight time if fixed feedback gains were used (Rossi 2003); obviously, this is undesired. Conversely, the gains would vary in a strongly irregular profile if a specific controller design was applied for each time of flight – an equally inappropriate behavior which could conduct to a bad transient performance.

The solution implemented for the Brazilian VLS consists of calculating the feedback gains (by the means of a given technique, to be further presented) for a specific analysis instant, adopted here, as the instant when the vehicle breaks the sound barrier, i.e., the transonic ($t = 25$ s), and to compare the system with the generic linear time-invariant transfer function $G_{ref}(s)$ given by (Eq. 9),

$$G_{ref}(s) = \frac{K(s + p_0\eta)}{(s + p_0)(s^2 + 2\zeta\omega_n + \omega_n^2)} \tag{9}$$

By comparing Eqs. 4 to 9, it is possible to extract the reference parameters K, η, ζ, ω_n and p_0, as follows (Eqs. 10 to 13),

$$K = -\mu_\beta K_P \tag{10}$$

$$\eta = \frac{K_I}{K_P p_0} \tag{11}$$

$$\omega_n = \sqrt{\frac{-\mu_\beta K_I}{p_0}} \tag{12}$$

$$\zeta = \frac{-\mu_\beta K_D + p_0}{2\omega_n} \tag{13}$$

where p_0 is the purely real root of the polynomial (Eq. 14),

$$p_0^3 + \mu_\beta K_D p_0^2 - (\mu_\alpha + \mu_\beta K_P)p_0 + \mu_\beta K_I = 0 \tag{14}$$

Once the reference parameters are determined, some of them are considered fixed (not all parameters can be fixed, since we only have three degrees of freedom) and used to calculate the feedback gains for the remaining analysis intervals, each one with its own μ_α and μ_β parameters, i.e. (Eqs. 15 to 17),

$$K_P = \frac{-\mu_\alpha + 2\zeta\omega_n p_0 + \omega_n^2}{\mu_\beta} = \frac{-K}{\mu_\beta} \tag{15}$$

$$K_I = \frac{-\omega_n^2 p_0}{\mu_\beta} = \frac{-K p_0 \eta}{\mu_\beta} \tag{16}$$

$$K_D = \frac{-2\zeta\omega_n + p_0}{\mu_\beta} \tag{17}$$

From the theoretical standpoint, what this strategy aims to perform is to impose a time-invariant dynamic behavior to the system (in practice, this is only possible by fixing all the reference parameters). This is achieved by freezing the poles of the closed-loop system for all instants of the analysis; besides making the feedback gains vary as functions of μ_α and μ_β.

LINEAR QUADRATIC (LQ) METHODOLOGY

As mentioned in the introductory part of this communication, the methodology currently employed for computing the feedback gains of the Brazilian VLS attitude controller (at the moment of the transonic), is the linear quadratic (LQ) methodology.

This methodology consists of determining the feedback gains that minimize the J_{LQ} cost function given by (Eq. 18),

$$J_{LQ} = \int_0^\infty [z^T(t)Qz(t) + \beta^2(t)R]dt \tag{18}$$

where z is the state vector defined in Eq. 7, and Q and R are weighting matrices that determine the importance of the states and control in the cost function minimization process, respectively.

The great advantage of the LQ methodology, as derived from the optimal control theory, is that it guarantees large stability margins, namely, gain and phase margins of at least 6 dB and 60 deg, respectively, if all the states are perfectly known (Levine 1996). Conversely, the performance of the temporal response is quite dependent on the choice of Q and R matrices, which, for being generally empirically performed, is greatly dependent on the designer's experience (Brito and Leite Filho 2005).

According to Ramos *et al.* (2003), for the Brazilian VLS attitude controllers, suitable values for the Q and R matrices are (Eqs. 19 to 20),

$$Q = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.2 \end{bmatrix} \tag{19}$$

$$R = 0.4 \tag{20}$$

As introduced in preceding Sections, the main purpose of this communication is to present (and analyze) alternative tuning techniques for the computation of the attitude controller feedback gains, which eliminate the empiricism associated to the choice of the Q and R matrices in the LQ methodology.

These alternative techniques, presented in sequence, are based on the minimization of different performance indexes (or optimality criteria), and are translated, as will be shown, in different dynamic behaviors for the concerned system.

INTEGRAL ABSOLUTE ERROR (IAE) INDEX

The first performance index addressed in this communication is the IAE index, which translates in the minimization of the following cost function (Eq. 21):

$$J_{IAE} = \int_0^\infty |e(t)|dt \tag{21}$$

where e is the error signal, i.e., the difference between the setpoint angle and the measured angle.

As argued by Palm (1986), the use of the IAE performance index in control systems design generally implies a major concern with the magnitude of the error, despite its duration/persistence, and the moment it occurs. In some cases, the IAE index is considered poorly selective.

INTEGRAL OF TIME MULTIPLIED ABSOLUTE ERROR (ITAE) INDEX

The ITAE performance index, originally proposed by Graham and Lathrop (1953), aims to increase the selectivity of the IAE index by assigning higher weight to the errors occurred at later time instants. The cost function to be minimized, in this case, is (Eq. 22),

$$J_{ITAE} = \int_0^\infty t|e(t)|dt \tag{22}$$

The ITAE index is widely used in the literature for control systems design because it allows optimal feedback gains to be easily calculated by direct comparison with tabulated transfer functions. For this purpose, the system under analysis needs to fit into one of the following transfer functions (Eqs. 23 to 25) (Chen 1993):

$$B_0(s) = \frac{b_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0} \tag{23}$$

$$B_1(s) = \frac{b_1 s + b_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0} \tag{24}$$

$$B_2(s) = \frac{b_2 s^2 + b_1 s + b_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0} \tag{25}$$

Since, for the particular case of the Brazilian VLS, the closed-loop transfer function does not fit into the Equations presented in Eqs. 23 to 25, the calculation of the feedback gains by the ITAE index, as well as for the other indexes (to be presented), has to be carried out numerically, by the means of recursive algorithms.

INTEGRAL SQUARED ERROR (ISE) INDEX

The ISE performance index is very similar to the IAE, except for the fact that the error module is replaced by the quadratic error. The cost function to be minimized is (Eq. 26),

$$J_{ISE} = \int_0^\infty e^2(t)dt \tag{26}$$

Similar to the IAE index, the ISE index implies a major concern about the magnitude of the error and is, in most cases, directly related to the energy consumption of the system (Palm 1986).

INTEGRAL OF TIME MULTIPLIED SQUARED ERROR (ITSE) INDEX

Finally, the last performance index investigated in this communication is the ITSE index, which has been originally designed to increase the selectivity of the ISE index (Chen 1993). It is calculated by the following cost function (Eq. 27),

$$J_{ITSE} = \int_0^\infty te^2(t)dt \tag{27}$$

RESULTS AND DISCUSSION

In this Section, we present the figures of merit adopted for comparing the investigated tuning techniques, as well as some simulation results.

COMPARISON CRITERIA

In order to establish a reliable comparative analysis between the investigated tuning techniques, different figures of merit, individually important for the overall performance of the system, were chosen, namely: the rising time T_R, the settling time T_S, the maximum overshoot O_M (all of them for an unit step input); and the phase and gain margins, M_P and M_G, respectively (for the open loop system).

As explained by Ogata (1997), the rising time is an indicator of the rapidity of the closed loop system response, and ideally, it shall assume values as small as possible. According to Silva *et al.* (2014), however, for the specific case of satellite launch vehicles, a rising time below a given limit value (adopted in this communication as 0.5 s) can compromise the physical integrity of the vehicle due to the excitation of its bending modes. For the same reason, the settling time and the maximum overshoot are also desired to be minimal.

Concerning the stability margins, conversely, Chen (1993) suggests that they shall assume values as large as possible in order to guarantee the stability of the system when other elements, not considered in this preliminary phase of design, such as filters and the actuators and sensors dynamics, are included in the control system. According to Ogata (1997), recommended gain and phase margins (in open loop) are at least 6 dB and 60 deg, respectively.

Finally, a last comparison criterion that has to be considered refers to the maximum nozzle deflection β_{max}. It is known, experimentally, that in order to the actuators remain within the operating range considered linear, we must have $\beta_{max} < 4$, for a unit step input (Silva and Leite Filho 2013).

By manipulating Eqs. 2 and 4, we can determine the parameters that influence the nozzle deflection (Eq. 28),

$$T(s) = \frac{\beta(s)}{\theta_{ref}(s)} = \frac{\beta(s)}{\theta(s)}\frac{\theta(s)}{\theta_{ref}(s)} = \frac{G_{CL}(s)}{G_S(s)} = \frac{K_P s^3 + K_I s^2 - \mu_\alpha K_P s - \mu_\alpha K_I}{s^3 - \mu_\beta K_D s^2 - \left(\mu_\alpha + \mu_\beta K_P\right)s - \mu_\beta K_I} \tag{28}$$

The mission event timetable demands that controller shall be started a little bit before the rocket ignition. Hence, there is a small amount of time where the control system is active but without useful propulsive control force. If a wind gust reaches the vehicle, moving it slightly in a lateral direction, the control system will actuates, providing an actuator deflection even though there is not an effective correction force (the propulsion is off). Because of this, the maximum nozzle deflection normally occurs at the beginning of the lift off in a regular flight (Brito *et al.* 2005). With this fact in mind, the initial value theorem (when $t = 0^+$) can be applied (Palm 1986),

$$\beta_{max} = \beta \tag{29}$$

As can be verified in Eq. 29, the maximum nozzle deflection is driven by K_p. Consequently, a requirement for the attitude controller design is (Eq. 30),

$$K_{P_{max}} < 4 \tag{30}$$

Thus, in order to ensure that the controllers tuned by each of the investigated techniques exhibit the same maximum nozzle deflection, a same K_p was stipulated for them, at all instants of the analysis.

SIMULATION RESULTS

Taking into account the aforementioned comparison criteria and control requirements, Table 1 summarizes the feedback gains, for the instant of transonic (t = 25 s), calculated by each tuning technique (using Eqs. 18, 21, 22, 26 and 27), as well as the values of the minimized cost functions (except for the LQ methodology, due to confidentiality matters). Similar to Brito and Leite Filho (2005), μ_α and μ_β, for the instant of transonic, were adopted as 1.4037 and –5.8006, respectively.

Table 1. Feedback gains and calculated cost functions.

Parameter	LQ	IAE	ITAE	ISE	ITSE
K_P	2.24	2.24	2.24	2.24	2.24
K_I	0.71	1.63	1.74	0.56	1.04
K_D	1.01	0.68	0.71	0.71	0.65
J	---	0.8286	0.7444	0.3856	0.2284

On the basis on the feedback gains calculated for the instant of transonic, Eqs. 10 to 14 were used to compute the parameters of the linear time invariant reference transfer function G_{ref}. These parameters, calculated for each tuning technique, are listed in Table 2.

Table 2. Calculated reference parameters.

Parameter	LQ	IAE	ITAE	ISE	ITSE
K	12.9878	12.9933	12.9933	12.9933	12.9933
η	0.7052	0.6482	0.6142	0.8005	0.7402
ω_n	3.0263	2.9020	2.8250	3.2251	3.1013
ζ	0.8949	0.4862	0.5051	0.5901	0.5067
p_0	0.4479	1.1227	1.2647	0.3123	0.6272

Figures 2 and 3 present the step response and frequency response (in open loop) for the controllers tuned by each of the investigated techniques at the instant of transonic.

In order to analyze the dynamic behavior of the system for the entire vehicle flight, in terms of the previously defined figures of merit, we employed Eqs. 15 to 17 and the corresponding μ_α and μ_β parameters (not shown in this communication due to confidentiality matters) to calculate the feedback gains for all instants of analysis. These gains can be seen in Figs. 4 to 6.

Finally, Figs. 7 to 11 present the time evolution of the previously defined comparison criteria for the controllers tuned by each of the investigated techniques.

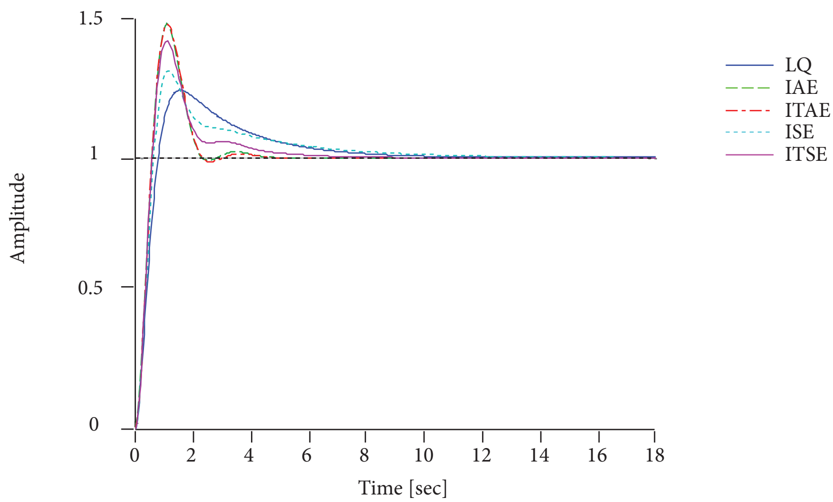

Figure 2. Step response at t = 25 s.

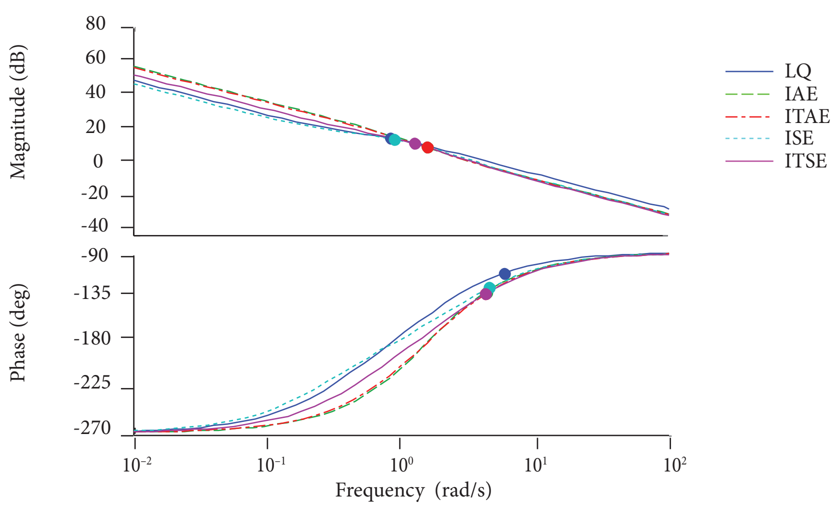

Figure 3. Frequency response at t = 25 s.

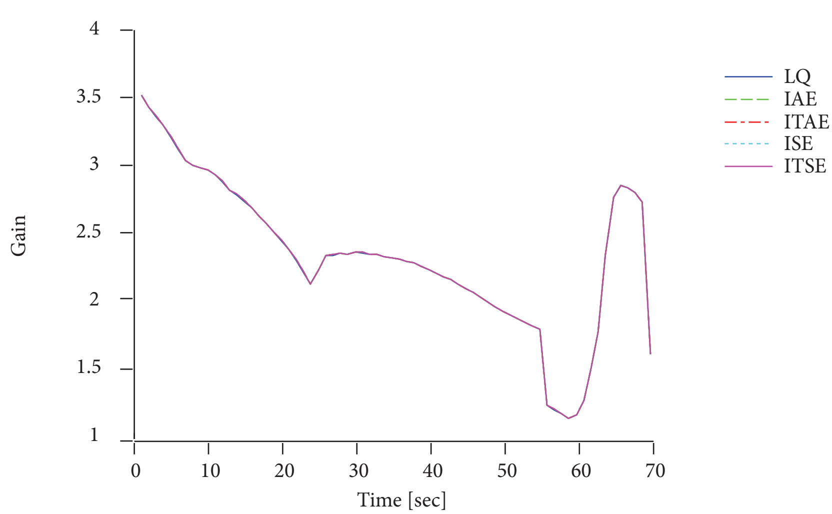

Figure 4. Proportional gain.

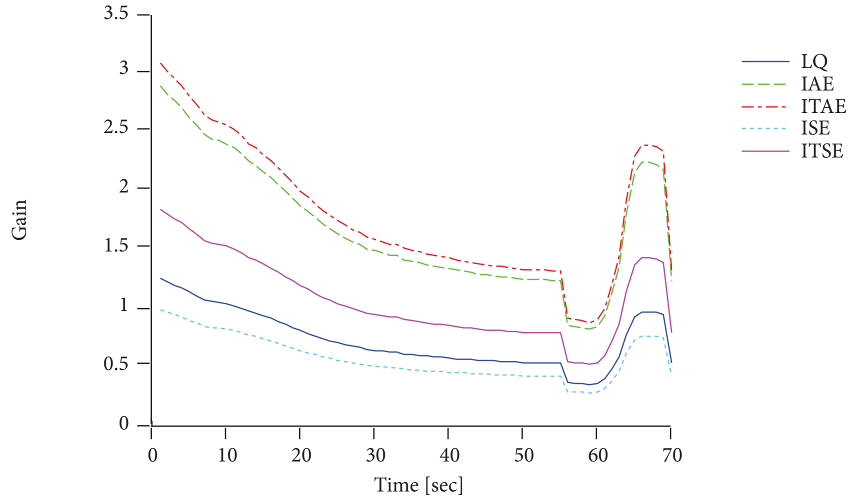

Figure 5. Integral gain.

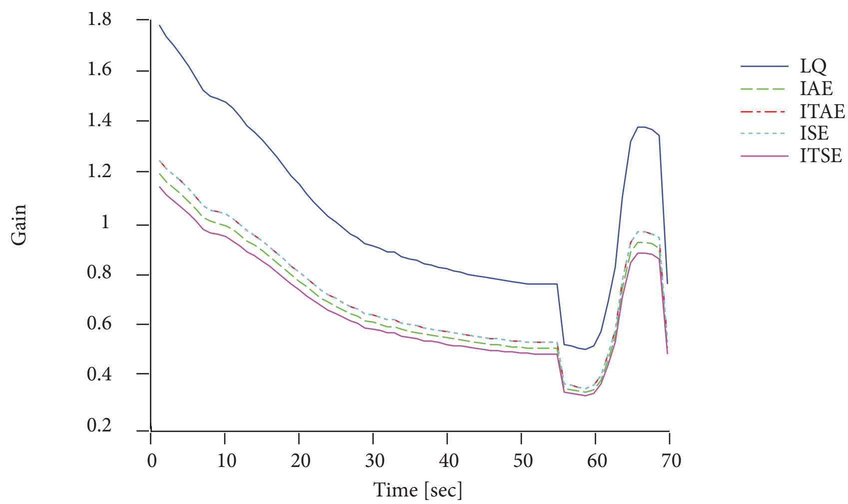

Figure 6. Derivative gain.

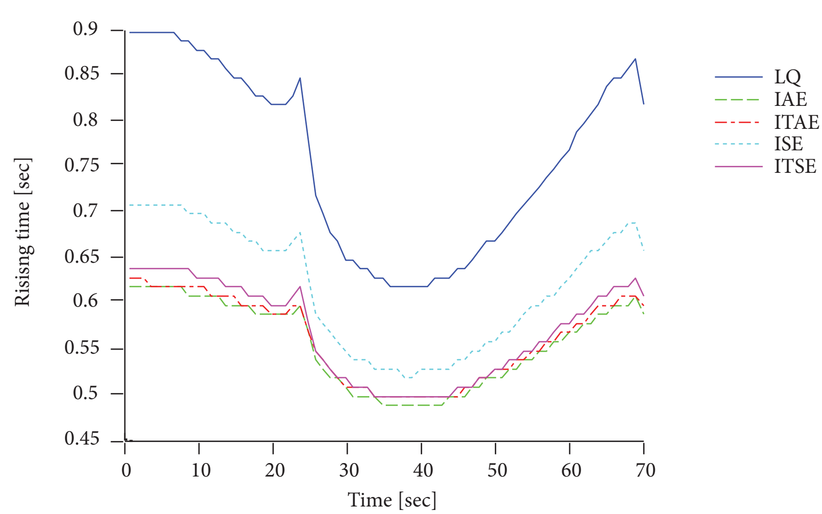

Figure 7. Rising time.

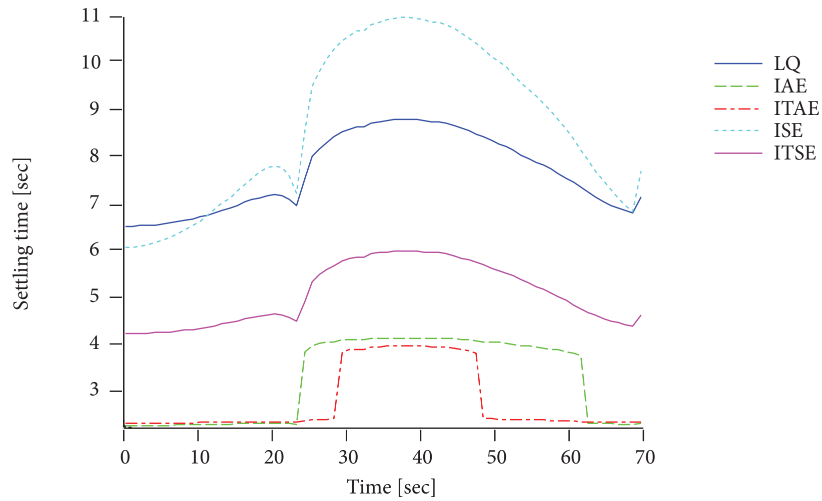

Figure 8. Settling time.

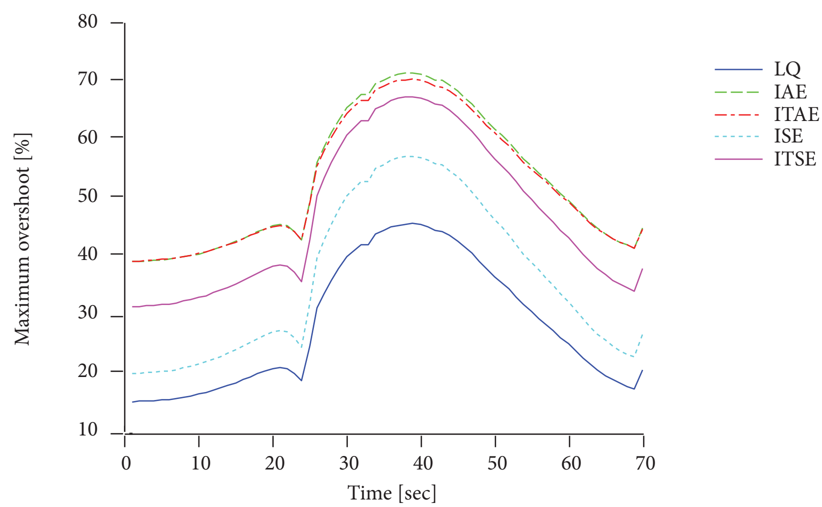

Figure 9. Maximum overshoot.

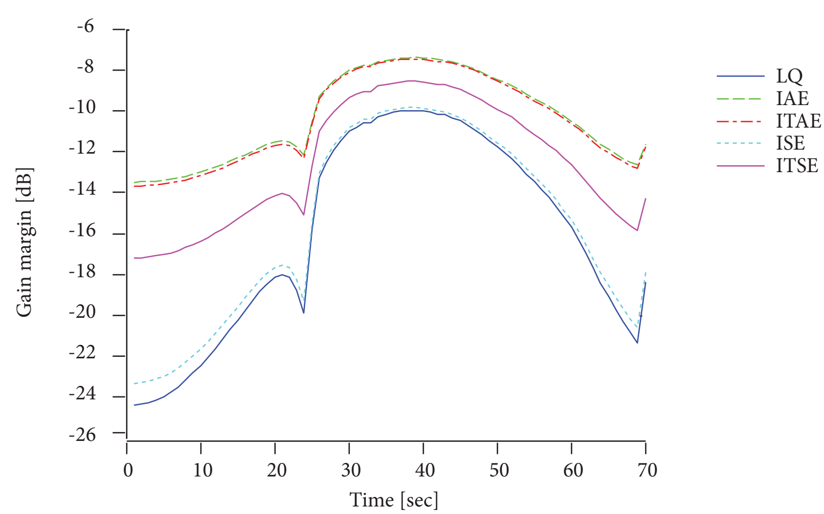

Figure 10. Gain margin.

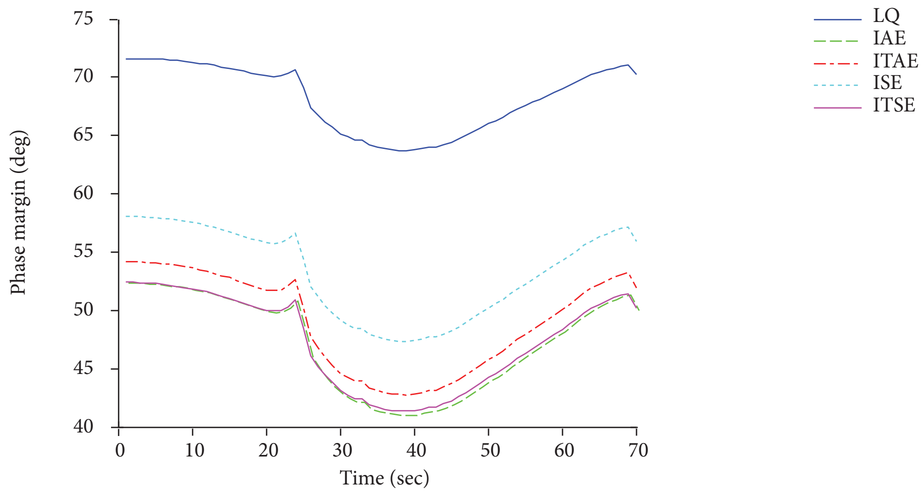

Figure 11. Phase margin.

RESULTS DISCUSSION

As can be seen in Figs. 7 to 11, the use of different tuning techniques has led to different dynamic behaviors for the closed loop system.

From the rising time point of view, the IAE, ITAE and ITSE indexes resulted in faster responses which, however, excessively approached the limit rising time established in preceding Sections. Therefore, we can consider that, for this particular figure of merit, the best results were those obtained by the LQ methodology.

Regarding the settling time and the maximum overshoot, the controllers tuned by the ITAE index and the LQ methodology, respectively, proved to be superior. Conversely, regarding the gain margin, we can verify that the best results were those obtained by the LQ methodology and the ISE index, simultaneously. Finally, concerning the phase margin, the LQ methodology proved to be considerably superior to the others, being the only one able to produce phase margins above 60 deg for all flight instants (as was already expected for this methodology).

By globally analyzing the established comparison criteria and taking into account that, for satellite launch vehicles, the most important figures of merit are the rising time, the maximum overshoot, and the stability margins (Brito *et al.* 2005), it is possible to conclude that the most suitable tuning technique for the Brazilian VLS attitude controllers remains the LQ methodology. Despite the empiricism associated with the choice of Q and R weighting matrices, the use of this methodology resulted in appropriate rising and settling times, reduced maximum overshoot, and adequate stability margins.

As an additional conclusion, we can verify that the minimization of a given performance index (or cost function), used to generate the feedback gains for a closed loop control system, does not necessarily imply obtaining the best possible controller, since the characteristics optimized by the cost function are not necessarily the characteristics required for the concerned application. Furthermore, for the specific case of the Brazilian VLS attitude controllers, better results could have been obtained by the investigated indexes (IAE, ITAE, ISE and ITSE) if the physical constraints related to the maximum nozzle deflection were milder.

As a final remark we must highlight that, due to the various simplifications considered throughout this communication, the results presented hitherto, concerning the optimal choice of tuning techniques for satellite launch vehicle attitude controllers, should be considered as preliminary, and mainly valid for initial stages of the control system design process.

CONCLUSIONS

In this communication, a comparative analysis of tuning techniques for satellite launch vehicle attitude controllers has been presented. The first investigated technique, which is currently employed in the Brazilian Satellite Launch Vehicle (VLS), was the linear quadratic (LQ) methodology.

By defining relevant figures of merit for evaluating the overall performance of the system, namely, the rising and settling times, maximum overshoot, and stability margins, the performance of an attitude controller tuned by the LQ methodology was compared to that of controllers tuned by alternative techniques. Similar to the LQ methodology, these techniques consist of minimizing specific performance indexes, or cost functions, namely, the Integral Absolute Error (IAE) index, the Integral of Time Multiplied Absolute Error (ITAE) index, the Integral Squared Error (ISE) index, and the Integral of Time Multiplied Squared Error (ITSE) index.

By the means of simulation results, we verified that, for the particular case of the Brazilian VLS, with its inherent physical limitations (maximum nozzle deflection), despite sparse benefits produced by the alternative tuning techniques, in particular ITAE and ISE, the attitude controller tuned by the LQ methodology proved to be superior to the others. It is important to mention that such linear control techniques, performed in the time-varying manner discussed herein, already proved themselves appropriate in both simulations and previous flights. Although a launch vehicle is a complex nonlinear dynamic system, the simplifying considerations presented in this communication are not uncommon, or excessively strong, being applied in many rockets with similar characteristics. Proof of this is the good performance of the presented control methodology in two real VLS' flights.

As a suggestion for future works, we intend to improve the proposed comparative analysis by using a greater number of comparison criteria and the non-simplified model of the vehicle rigid body dynamics. Moreover including, in the simulations, dynamics as the effect of disturbances caused by wind gusts, and other non-linearities (Brito 2011), could greatly improve the robustness of the analysis. Finally, the investigation of more modern tuning techniques, as the one based on the minimization of the H_∞ norm, seems to be a very promising research topic for future works.

AUTHORS' CONTRIBUTION

Conceptualization, Silva F and Leite Filho WC; Methodology, Leite Filho WC, Brito AG and Silva AG; Investigation, Silva FO; Writing – Original Draft, Silva FO; Writing – Review and Editing, Leite Filho WC, Brito AG and Silva AG; Funding Acquisition, Leite Filho WC; Resources, Leite Filho WC; Supervision, Leite Filho WC.

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