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PHD THESIS SUMMARY

Adaptive control methods for launch vehicles

COMISIA DE DOCTORAT

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Contents

Key words: adaptive control, launch vehicle, model reference adaptive control, multi-model adaptive control, strictly positive real adaptive control system

Chapter 1. Introduction

Motivation

Launch vehicle control systems play an important role in payload delivery missions as they influence both the performance and operations of the launch vehicle. In general, for such aerospace structures, traditional controllers cannot provide the required performance [1]. One of the possible solutions used in recent years is adaptive control.

Recent studies show that there has been an increase in the total number of spacecraft launched into space, with a potential increase in the next decade [2], driven by the increasing use of small satellites in military, commercial or educational applications. Also, at the European level, the future directives of the ESA (European Space Agency - European Space Agency) involve the development of new technologies to reduce the cost, increase safety in flight and improve the performance of space transportation [3].

Objectives

The purpose of this PhD thesis is to analyze and develop adaptive control configurations for the control systems of launch vehicles.

Thesis organisation

To achieve the proposed objectives, this work is structured in 9 chapters, including this introduction. Chapter 2 contains a brief description of the Vega launcher, an analysis of the reference mission, as well as the specific requirements of the launch vehicle control systems. Chapter 3 presents the dynamic model of a generic launch vehicle. Chapter 4 is devoted to conventional control techniques. Chapter 5 studies the reference model adaptive control architecture. Chapter 6 presents an adaptive control structure with multi-model configuration. In Chapter 7, a positive real strict adaptive control structure was implemented. Chapter 8 includes the testing of the studied control architectures on the nonlinear model of the VEGA launch vehicle, as well as an analysis of their performances. Chapter 9 contains the conclusions, personal contributions and future research directions.

Chapter 2. Mission analysis

Rocket flight can be divided into two main phases: atmospheric and exo-atmospheric. The boundary between these two is located at about 120 km, and atmospheric forces can be neglected. Given that during the atmospheric flight, the performance of the launch vehicle will be influenced by its environment, it is necessary to model the atmospheric properties (temperature, pressure and density) with accurate approximations. Many atmospheric models have already been developed to meet the needs of launch vehicle design and trajectory analysis [4], [5].

Vega launch vehicle description

Vega is a launcher consisting of three solid propellant engines (P80, Zefiro 23 and Zefiro 9) that provide propulsion for the first three stages and a liquid propellant engine (Figure 1). Capable of placing between 300 and 2500 kg into orbit, the reference mission of the Vega launcher is to deliver a 1500 kg payload into a polar circular orbit at an altitude of 700 km.

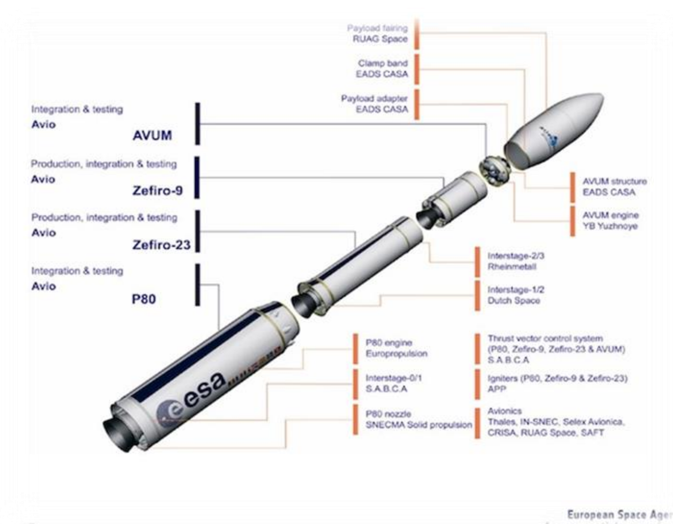

Figure 1: Vega Launcher components [http://www.esa.int/esapub/br/br257/br257.pdf]

The Vega launcher has a thrust vector direction control system (TVC- Thrust Vector Control) [6]. Due to the wide range of configurations and mission trajectories, command laws must be updated and adapted for each mission.

Trajectory

A typical Vega launcher mission can be divided into three main phases:

- The first phase involves the ascent of the vehicle into the low elliptical orbit (sub-orbital trajectory).
- In the second phase, the separation of the third stage and the placement of the satellite into orbit take place. Depending on the final orbit, one or more AVUM engine burns are required if changes in orbital plane or altitude are required.
- In the last phase of the mission, the AVUM is deorbited.

Perturbations

The disruptive effect of wind is a critical factor for any atmospheric launch phase. In general, it produces a significant degradation of the overall mission performance and induces structural loads that can cause the loss of the vehicle.

Specific control systems restrictions for launch vehicles as Vega

The TVC subsystem must ensure the stability of the steering commands while satisfying the demanding performance and stringent requirements in the presence of external disturbances.

Conclusions

Throughout this chapter I followed the definition of the launch vehicle for which the designed control schemes will be tested. Also shown were the phases of a typical flight, as well as the mission sequence in the case of the reference flight of the Vega vehicle. These are important in faithfully recreating the reference mission so that pitch and yaw attitude profiles are obtained.

Chapter 3. Equations of motion

Rigid-body dynamics

For the design of the automatic control system of the launcher, it is necessary to determine a mathematical model of its dynamics, also called "design model". The created model must contain the characteristic features of the vehicle, relevant from the point of view of automatic control.

Parameters and variables definition

A rigid, simplified model of the Vega launch vehicle is used to design the automatic control system. The linearized model used to design the AFCS of the Vega launcher for the pitch channel, assuming it to be a rigid body, is given by the equations of state:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \tag{1}$$

where $A = \begin{bmatrix} 0 & 1 & 0 \\ a_6 & 0 & a_6 / v \\ -a_1 & 0 & -a_2 \end{bmatrix}$, $B = \begin{bmatrix} 0 & 0 \\ -k_1 & a_6 \\ -a_3 & a_2 v \end{bmatrix}$, $C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$, $D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$, $x^T = \begin{bmatrix} \theta & \dot{\theta} & \dot{z} \end{bmatrix}$,

$u = \begin{bmatrix} \delta \\ \alpha_w \end{bmatrix}$ consists of the commanded actuator deflections δ and α_w is the wind incidence angle,

$y = \begin{bmatrix} \theta & \dot{\theta} & \dot{z} \end{bmatrix}^T$ is the vector of outputs.

Flexible modes

Flexible launcher modes contribute to the deterioration of the launcher's stability performance.

Conclusions

I have aimed throughout this chapter to capture the equations that describe the complex motion of the launch vehicle. I started from the dynamics of the rigid solid, later modeling the flexible modes that appear due to the structural flexibility. The first three flexible modes were considered, which, according to the specialized literature, are dominant in modeling the launcher dynamics.

Chapter 4. Conventional design of automatic control system for pitch/yaw motion

PD controller

Considering the full rigid model and neglecting the flexible modes and its filters, the closed loop that is used to design the pitch control system using the Proportional-Derivative (PD) controller is shown in Figure 2.

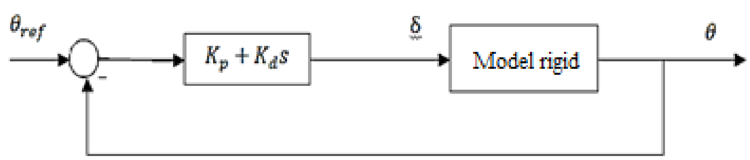

Figure 2: PD architecture

State feedback control

Another considered options is represented by the state feedback control.

Conclusions

In this chapter, it has been shown that PD-type control laws can guarantee the stability of the launch vehicle, providing good tracking performance.

However, the performance of this type of automatic control system is limited if the requirements for mitigating the effects of atmospheric disturbances are taken into account. PD-type command laws may represent an acceptable solution in some situations due to the simplicity of implementation. It was highlighted that even in this case, some performances can be improved regarding the robustness of the stability due to the mitigation of the effect of atmospheric disturbances, but also the limitation of the amplitude of the angle of incidence and the commands.

Chapter 5. Design of reference model adaptive automatic control system for pitch/yaw motion

Among the various adaptive control laws, adaptive augmentative control (AAC), which is a type of reference model adaptive control, is very commonly used in control configurations.

In the following, I introduced for the VEGA launcher studied in the present paper, an adaptive control architecture similar to the one proposed in [7]. This adaptive strategy was successfully used in flight tests on an F/A-18 aircraft [8]. The control system of the Space Launch System (SLS) is based on a classical basic controller, which is supplemented by an adaptive control law. The augmentative adaptive control system uses a multiplicative law.

For nominal flight conditions (maximum pressure area, no wind influence, rigid body) the PD+AAC controller performance will be analyzed compared to PD law (Figure 3).

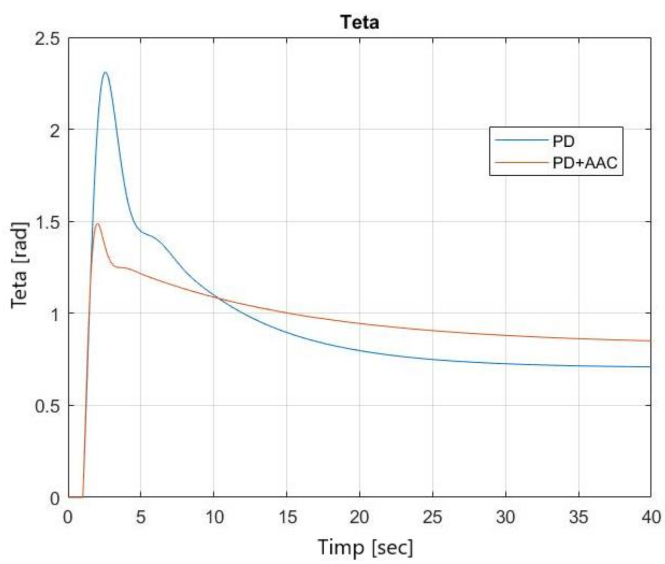

Figure 3: Step response

The simulation results show that both the PD controller and the adaptive controller provide system stability not only in the nominal case, but also for dispersions of up to 20% in the model parameters. For the extreme situations, instead, it is observed that the adaptive controller gains a much higher weight than the classical control component, performing better compared to the classical PD controller in terms of overshoot and steady-state error. Although, the adaptive controller has not completely eliminated the steady-state error, it ensures a good stabilization of the system.

Flexible modes influence

The structure used to include flexible modes in the model is the one proposed by Du [9] and is represented in Figure 4.

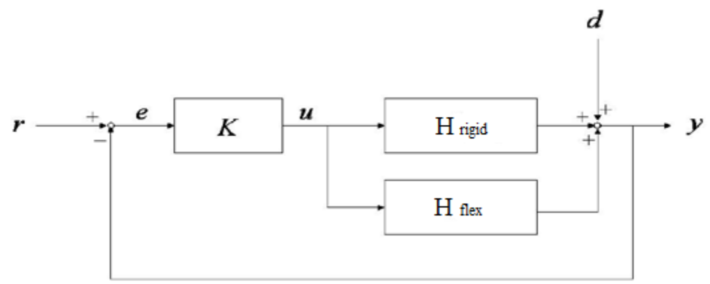

Figure 4: Block diagram of rigid body and flexible modes

where

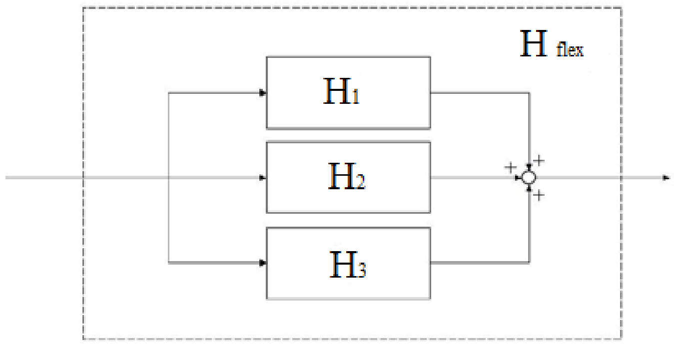

Figure 5: Block diagram of flexible modes

and $H_j(s) = \dfrac{K_j}{s^2 + 2\zeta_j \omega_{n_j} s + \omega_{n_j}^2}$, where $j = 1...3$ indicates the index of the flexible mode, and K_j, ξ_j and ω_{n_j} are the coresponding gain, amplificarea, damping coefficient and natural pulsation of the respective flexible mode [9].

To stabilize the system, a filter is added to remove the effect of flexible modes. Two options were considered: adding a filter for each flexible mode, and the second option is given by adding a filter on the feedback after θ. The latter was considered because adding such a filter for each mode could interfere with overall system performance.

Since a certain frequency was required to be attenuated, two types of filters were considered: a notch filter (band-stop type) and a maximum flat (Butterworth) filter.

The step input response for the control algorithm containing the Butterworth filter shows good results in all several cases tested, but in the case of the notch filter, a new filter design is required for each case.

Conclusions

Using the adaptive architecture proposed by Orr [7], a reference model adaptive control law was incorporated into the system containing the designed classical PD controller to increase performance and handle contingencies. The results of the simulations performed show that the adaptive boost provided sufficient performance improvement and avoided vehicle loss in both nominal and extreme situations.

Since the launch vehicle can become unstable if its flexible modes are not taken into account, simulations were performed considering the first three bending modes. To regain the stability of the vehicle, two types of second-order low-pass filters, a notch filter and a Butterwoth filter, are proposed. The simulation results show that the adaptive control system containing one of these types of filters for the Vega launcher can guarantee the stability without affecting the system performance. Several cases were tested in the atmospheric phase of flight, proving the robustness of the control system containing the Butterworth filter. To maintain the stability of the control system using the notch filter, additional adjustment of the filter coefficients is required.

Personal contributions:

- implementation of the command law with the reference model in the case of the Vega launcher;

- defining the filters included in the the control law;

- designing filters to mitigate the effect of flexible modes.

Chapter 6. Design of multi-model adaptive control

Classical multi-model adaptive control (MMAC) systems [10] use controllers connected to multi-model adaptive estimation (MMAE) [11] schemes, considering the information received in real time to decide on the controller with the best performance in the case studied, through various algorithms or switching logics.

The RMMAC control system structure is a multi-model approach that computes and uses the posterior probabilities of the model's uncertain parameters to switch or combine the outputs of a set of controllers. Each controller is designed for a certain range of uncertainty, and the identification subsystem uses a bank of Kalman filters (KF).

The RMMAC control architecture uses the techniques found in the classical MMAE control structure, with the difference that the Kalman filters only generate residuals, they do not also render the estimated states, acting as an identification subsystem.

Testing RMMAC

Eleven cases were defined at the time of the test scheme to take into account the two uncertainty intervals for each uncertain parameter in the linearized model of the launcher, plus the nominal case. The nominal case contains the nominal values of the parameters, considering an uncertainty interval of ±20% of their value.

For testing the RMMAC scheme, the model parameters will be given values that describe the vehicle movement and the probabilities generated by the probability calculation algorithm will be checked. The system response must be stable, and the corresponding controller to be chosen accordingly.

The simulations were carried out in Matlab/Simulink, and the control structure has the form:

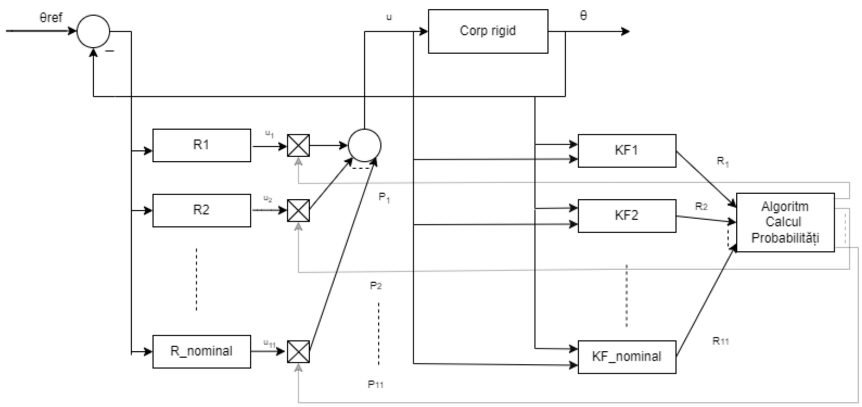

Figure 6: RMMAC control scheme

where R_i corresponds to the controller for case i, KF_i corresponds to the KF for case i, R_i represents the generated residual by each Kalman filter, and $i = 1 \dots 11$.

The parameter values for the tested cases were chosen so that when the controller designed for the nominal situation does not cope, the controller designed for the chosen situation intervenes, as exemplified in the following case:

- $a_6 = 2.018$

The probabilities obtained with the probability calculation algorithm are:

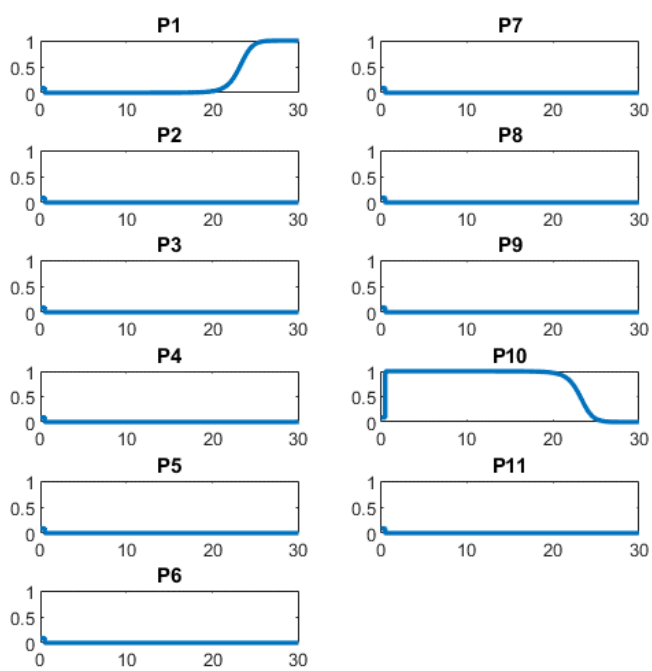

Figure 7: The probabilities in case 1

It is observed that the identification of the corresponding model takes place in 21 seconds. The response on the pitch channel of the launcher to step command is:

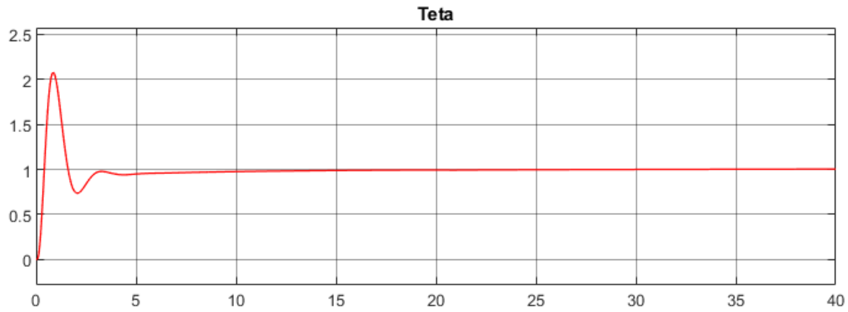

Figure 8: Step command (case 1)

Contrary to the case of the control scheme containing the controller designed for the nominal situation, if the parameter a_6 takes extreme values, the system becomes unstable.

To increase the efficiency of the RMMAC algorithm, a buffer was used to store the values of the residuals from the last 10 iterations. These values are used in the next calculation step to identify the appropriate control model. The identification of the corresponding model is achieved much faster, the identification time being reduced by approximately 1 second for cases 6, 8-10, by 2 seconds in case 11, by 5 seconds for case 3 and by more than 12 sec, respectively 20 sec for cases 5 and 1.

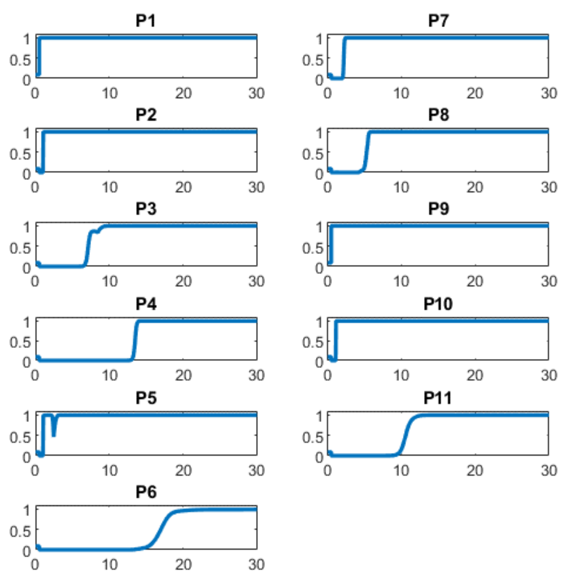

Figure 9: Probabilities with RMMAC control

Conclusions

Throughout this chapter I have implemented an RMMAC-type control structure for the VEGA space launcher. I studied eleven cases, considering a variation of ±40% for the uncertain parameters describing the launcher model. Thus, I designed eleven Kalman filters to lead to the identification of the appropriate case and eleven robust controllers to ensure the stability and performance of the system. Although in some situations the identification takes place after 20 seconds, this has been done correctly, ensuring the possibility of implementing new cases to cover unforeseen situations.

In order to increase the performance of the RMMAC control structure, I added a buffer so that the likelihood algorithm can take in more residual data. The results of the simulations showed that the time to identify the corresponding pattern decreased considerably.

Since RMMAC uses multiple models, the performance requirements determine the number of models. This dependence can lead to an excessive number of models, which can make difficult the real-time calculation of the order law.

Personal contributions:

- the design of the Kalman filters needed for the multi-model adaptive control scheme;

- designing μ-synthesis controllers;

- implementation of the RMMAC adaptive control law in the case of the Vega launch vehicle;

- modifying the RMMAC adaptive control law to improve the results, by adding a buffer containing a history of the residual data, leading to the identification of the corresponding model in a faster time.

Chapter 7. Design of strictly positive real adaptive control system for launching vehicles

In this chapter, the possibility of designing a strictly positive real adaptive control system for the pitch/yaw dynamics of the launch vehicle is analyzed.

The interest for this class of systems is determined by the robustness properties of the stability of strictly positive real systems (SPR) and some theoretical results demonstrated in [12].

Starting from the properties of strictly positive real systems, as well as the Real Positivity Lemma [12], [13], the following feedback control configuration after the measured output is considered.

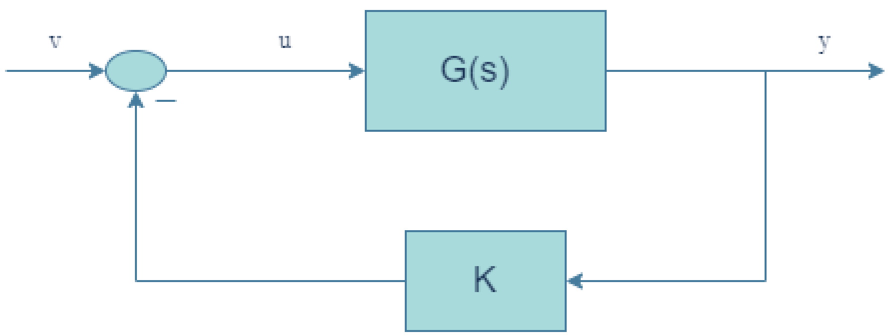

Figure 10: Closed-loop system

where K is a constant output feedback, and $G(s)$ is the transfer function of the linear system described by the state-space equations:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{2}$$

where $x \in \mathbb{R}^n$ is the state vector, $u, y \in \mathbb{R}^m$ are the control vector, and the output vector, and $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, $C \in \mathbb{R}^{m \times n}$ are constant matrices of appropriate dimensions, such as the pair (A, B) is controlable, and (C, A) is observable.

The equivalent system of the closed-loop system described in Figure 10 can be expressed such as:

$$\begin{cases} \dot{x}(t) = A_K x(t) + Bv(t) \\ y(t) = Cx(t) \end{cases} \quad (3)$$

where $A_K = A - BKC$.

According to the Real Positivity Lemma, the transfer function $T(s) = C(sI_n - A_K)^{-1}B$ of the resulting system (3) is strictly positive real if there is a matrix $P = P^T > 0$ such that the next two conditions are fulfilled :

$$PA_K + A_K^T P < 0 \quad (4)$$

$$PB = C^T \quad (5)$$

The following result, the proof of which can be found in [12], gives conditions for the existence of a feedback after the output such that the equivalent transfer function of the system resulting from Figure 10 to be strictly positive real.

Theorem 1 [12]: There is a constant matrix K such that the closed-loop system $T(s)$ is strictly positive real if and only if:

$$B^T C^T = CB > 0 \quad (6)$$

And if there exists a positive definite matrix X such that:

$$C_\perp^T herm\{B_\perp X B_\perp^T A\} C_\perp < 0 \quad (7)$$

where $M_\perp$ is the orthonormal null space of M, that is $M_\perp$ satisfy the conditions $M_\perp^T M = 0$ and $M_\perp^T M_\perp = I$, where I is the identity matrix.

According to [12], if the conditions of Theorem 1 are satisfied, there exists a constant matrix K^* such that the transfer function of the resulting system from Figure 10 to be SPR.

In order to be able to apply an adaptive control law based on the results presented above, it was aimed to satisfy the conditions of Theorem 1. Thus, it is necessary, first of all, that the dimension if the control vector to match that of the output vector. For this purpose, the PD coefficents developed in Chapter 4 are used.

Using semidefinite dynamic programming techniques implemented in the MATLAB software package, it is shown that the conditions of a strictly positive real system are satisfied.

Thus the adaptive control law can stabilize the system. Next, the results of the simulations obtained with the adaptive control law, will show that it regulates its output vector to zero, given the simulations performed in Matlab/Simulink.

In Figure 11 the time response of the linearized launcher dynamics to a nonzero initial condition is presented, $x = [0.03\ 0.03\ 0]^T$, considering $\Gamma = 1000$. It is observed that the system is stable, having a small rise time. For these simulations, the nominal flight condition (maximum pressure area, without the influence of wind and flexible modes) was considered.

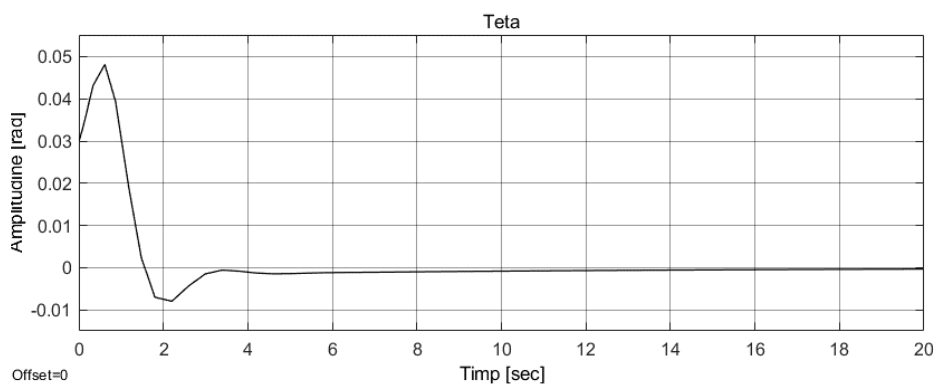

Figure 11:Teta output for $\theta_{ref} = 0$ *rad and* θ_0 *=0.03 rad*

To analyze the influence of the wind on the space launcher, the time response of the pitch angle was determined, for $\alpha_\omega = 0.025\ rad$, considering the wind velocity of 14 $m/\sec$. This value was chosen according to the moment of time at which the linearization of the dynamic model of the launcher was made, from the velocity profile shown in [15]. The adaptive control law derived above ensures the stability of the launcher, and the values of lateral velocity and angle of incidence fall within the maximum allowable limits ($\dot{z} < 15 m/\sec$ and $\alpha < 3°$ for Vega launcher [16]) .

To analyze the influence of flexible modes, the structure proposed in [9] is used. The first three flexible modes were considered, for the nominal flight condition.

Robustness analysis of SPR-based adaptive control law

In order to be able to ensure the robustness of the order law, it will be checked, if for perturbations of the elements of the matrices A, B and C, if the SPR conditions are still met.

Given that the two conditions that ensure that the system is strictly positive real are still met, the command law ensures stability, as can be seen in Figure 12.

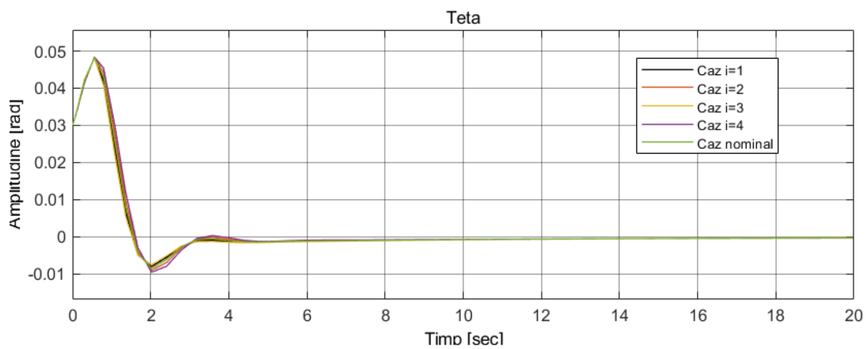

Figure 12: Teta output for $\theta_{ref} = 0$ *rad and* θ_0 *=0.03 rad*

Since the adaptive control law does not ensure good tracking, in order to solve this disadvantage, an integrator element was introduced. With this integrating element, the steady-state error tends to zero, but with a large overshoot.

In order to be able to improve the pitch angle overshoot, a variation of the adaptive law was considered, by adding a reference model, which represents the desired dynamics of the system. The reference model is the one used in the case of the control algorithm presented in [17]. This is implemented in Simulink as a 2nd order transfer function, $H_{ref}(s) = \frac{\omega_{ref}^2}{s^2 + 2\zeta_{ref}\omega_{ref}s + \omega_{ref}^2}$, for which the following values were used: $\xi_{ref} = 0.8$ and $\omega_{ref} = 0.942$. Thus, the adaptive control law will be adjusted based on the error between the output of the measured output and the output of the reference model.

Se observă că stabilitatea este în continuare menținută. The response of the system when using the reference model adaptive control law, at command with zero amplitude and non-zero initial conditions, is illustrated in Figure 13. It is observed that stability is still maintained.

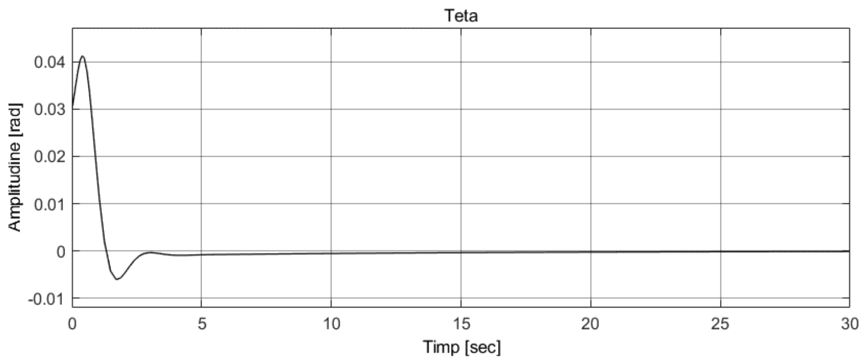

Figure 13: Teta output for $\theta_{ref} = 0$ *rad and* θ_0 *=0.03 rad*

For an input of $0.1\,rad$, the responses of the systems in the case of the initial adaptive law and in the case of the reference model configuration are presented comparatively.

It is observed that the response in the second case performs much better on pitch overshoot, proving the effectiveness of the SPR adaptive control algorithm with reference model.

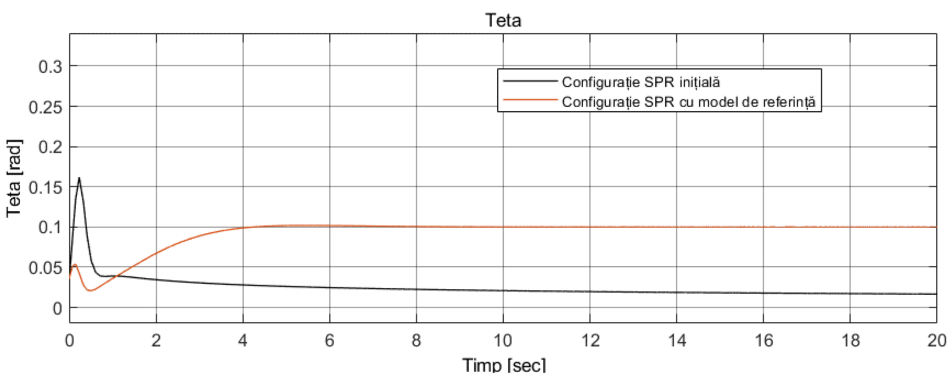

Figure 14: Teta output for $\theta_{ref} = 0.1$ *rad and* θ_0 *=0.03 rad*

It is thus observed that for all the cases tested, the stability of the system is maintained, and the lateral velocity and angle of incidence have values that fall within the predetermined ranges.

Conclusions

Throughout this chapter I have implemented an adaptive control structure based on the positivity properties of the transfer matrix, considering the Vega launcher as a case study. Since, in order to be able to apply the command law to the launch vehicle, it is necessary for it to comply with conditions applicable to a positive real system, it was necessary to ensure the SPR conditions. This was achieved by modifying the output of the system, using the coefficients of the previously designed classic PD controller. It has been shown that the system thus becomes positive real and that the designed control structure provides stability both for the rigid body and for the case where its vibration is taken into account (the first three flexible modes were used). The stability of the system has been tested when the coefficients describing the launcher motion vary, demonstrating that the positive real system conditions are still respected in these cases as well.

Since for different values of the input signal, there is considerable steady-state error, it has been considered to introduce an integral component on the forward loop so as to reduce this error. Also, a configuration with a reference model was proposed for which it was demonstrated, through the results of the simulations performed in Simulink, that it ensures the stability of the system and its performance is satisfactory.

Personal contributions:

- Analysis of the adaptive control scheme from the point of view of strictly positive real systems;
- Ensuring the SPR conditions for the pitch channel of the launcher;
- Application of an SPR adaptive control law to the launch vehicle;
- Application of the positive strict real system relationship for robustness analysis;
- Proposing two new adaptive control law configurations (by adding the integrator element and adding a reference model) to eliminate the steady-state error.

Chapter 8. Control testing on non-linear model

The control algorithms were successfully tested on a linearized model in the maximum dynamic pressure area, being the most sensitive area. However, tests of the developed controllers throughout the flight are needed to be able to confirm the results obtained. For this, the nonlinear model of the Vega launcher imported from ASTOS was used, in Matlab/Simulink, the latter being the work program used in the implementation and testing of the control algorithms.

ASTOS (Analysis, Simulation and Trajectory Optimization Software) is a simulation and optimization environment to simulate and optimize trajectories for a variety of complex multi-phase optimal control problems. It provides an s-function in Simulink that allows it to act as an environment and dynamics block within a GNC (Guidance, Navigation and Control) environment within Simulink [19].

In order to test the control algorithms under the same conditions, the reference mission of the Vega launcher was preserved.

Adaptive control algorithms simulations on rigid-body vehicle

Next, considering the nonlinear model exported from ASTOS (nominal scenario), the three adaptive control schemes will be tested, on the pitch channel. The flight portion considered will be up to 106.8 seconds, which is the moment when the first stage is jettinsoned. The parameters that describe the movement of the launcher change considerably after this moment, thus requiring the adjustment of the components of the control algorithms.

The following figure shows the implementation of the control system used to control the movement of the launcher:

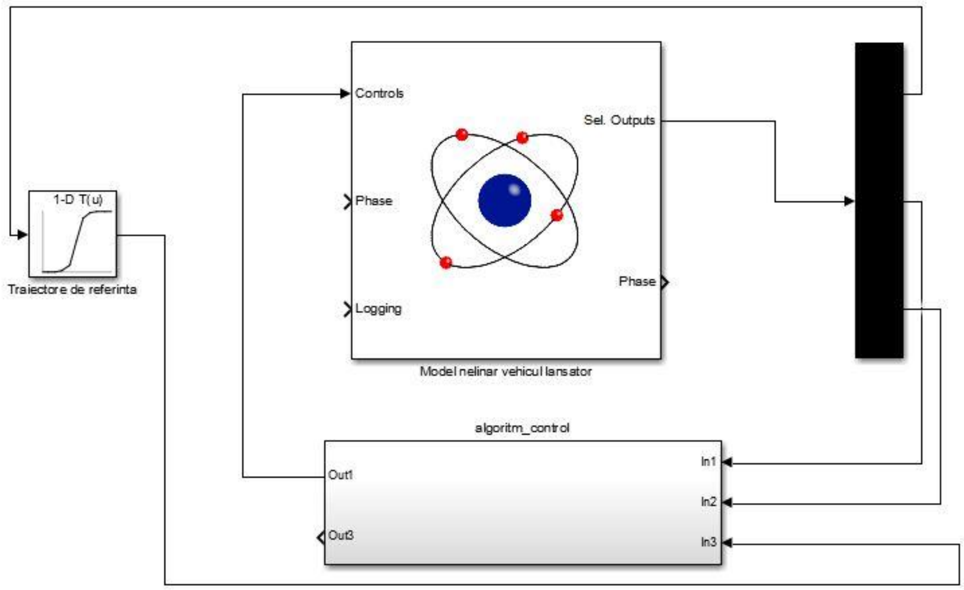

Figure 15: Control algorithm in Simulink using non-linear model

The simulation results show that the adaptive control algorithms with reference model, multi-model configuration and strictly positive real with integrator element and strictly positive real with reference model ensure the stability of the launcher, providing satisfactory results.

Adaptive control algorithms simulations on rigid-body vehicle in terms of robustness

To test the robustness of the system, the parameters characterizing the Vega launcher were changed. Thus, 100 simulations were run for each control algorithm, by means of the Batch-Mode Inspector work tool available in ASTOS, having as variables the thrust force of the P80 engine and the structural mass of the first stage, these receiving random values in a specified range of nominal values.

Adaptive control algorithms simulations on rigid-body considering wind perturbations

To study the influence of wind on the launch vehicle, the nominal wind profile found in [21]. This profile was selected as such models are used for launch vehicle control design and evaluation.

Adaptive control algorithms simulations on flexible-body vehicle

Next, the control algorithms for which satisfactory results were obtained in the case of testing on the nonlinear model of the launcher considered as a rigid body, will be evaluated on the nonlinear flexible model of the launcher.

For these simulations, the MBS (Multibody dynamics) feature present in ASTOS was used. This allows the vehicle flexibility to be simulated by using LFD (Linearised Flexible Dynamics). This approach considers the flexibility of the vehicle as a whole and only in terms of vibration frequencies and modes. Vehicle flexibility is represented by a series of 2nd order equations of motion [22].

The results of the simulations performed with the four types of adaptive configuration are presented comparatively: with reference model, SPR with integrator element, SPR with reference model and multi-model considering the rigid and flexible launch vehicle respectively. It can be concluded that these control architectures preserve the performances of the rigid body testing case and the flexible case.

Conclusions

Throughout this chapter I have analyzed the performance of reference model, multi-model and SPR adaptive control architectures previously developed through Matlab/Simulink and ASTOS. This working environment allowed testing on the non-linear model of the launcher, considering the reference mission, until the time of first stage is jettinsoned.

The simulation has been considered up to this point because the coefficients describing the movement of the launcher change drastically and it is necessary to change the parameters of the control system.

Following the analysis on the nonlinear model, considering the rigid body launcher and the nominal conditions, it was found that the results are satisfactory in the case of adaptive control with reference model, SPR adaptive control with integrator element, SPR adaptive control with reference model and multi-model adaptive control.

To be able to check the influence of flexible modes, the first three flexible stages were considered and the flexibility of the launch vehicle was modeled by means of ASTOS and MBS. It was observed that the stability is maintained throughout the 106.8 seconds of flight and the performances are not diminished.

Since the control system has to deal with the uncertainties that may appear during the flight, simulations were carried out considering a random variation of the values of the parameters describing the first stage of the launcher. Thus, after 100 simulations, it was found that the developed control architectures provide satisfactory performance.

Also, to test the influence of perturbations, a wind profile used for control testing in the design phase of launch vehicles was added, finding that it did not influence the trajectory, as in the case of the tests carried out on the linear model, the results being satisfactory in the case of reference model adaptive configuration and multi model adaptive configuration. In the case of the SPR adaptive configuration, it is necessary to adjust the coefficients.

Personal contributions:

- Implementation of control schemes developed with the non-linear model of the launcher modeled by means of ASTOS;
- Analysis of control schemes based on non-linear model - rigid body;
- Robustness analysis of control schemes based on non-linear model - rigid body;
- Disturbance response analysis of control systems tested on a non-linear rigid body model;
- Analysis of control schemes based on non-linear model - flexible body.

Chapter 9. Results and conclusions

General conclusions

In order to fulfill the nine proposed objectives, I structured the thesis in nine chapters, including an introductory chapter for familiarization with the issue of adaptive control systems for launch vehicles, as well as a final chapter in which I described the results and conclusions, highlighting the author's main contributions.

Contributions

Personal contributions are presented succinctly, by chapter, as follows:

Chapter 1:

- Synthesizing from the specialized literature information on modern control systems used for space vehicles.

Chapter 2:

- Presentation of the stages of creating a control system;
- Presentation of a typical mission for space vehicles;
- Highlighting the characteristics of the Vega launcher as an industrial benchmark, as well as presenting the reference mission.

Chapter 3:

- Determination of the mathematical model that describes the movement of the launch vehicle considered as a rigid body;
- Modeling flexible modes;
- Defining the AFCS design model.

Chapter 4:

- Analysis of the PD design method in the case of space vehicles;
- Analysis of the state-feedback design method in the case of space vehicles.

Chapter 5:

- implementation of the command law with the reference model in the case of the Vega launcher;

- defining the filters included in the the control law;

- designing filters to mitigate the effect of flexible modes.

Chapter 6:

- the design of the Kalman filters needed for the multi-model adaptive control scheme;

- designing μ-synthesis controllers;

- implementation of the RMMAC adaptive control law in the case of the Vega launch vehicle;

- modifying the RMMAC adaptive control law to improve the results, by adding a buffer containing a history of the residual data, leading to the identification of the corresponding model in a faster time.

Chapter 7:

- Analysis of the adaptive control scheme from the point of view of strictly positive real systems;
- Ensuring the SPR conditions for the pitch channel of the launcher;
- Application of an SPR adaptive control law to the launch vehicle;
- Application of the positive strict real system relationship for robustness analysis;
- Proposing two new adaptive control law configurations (by adding the integrator element and adding a reference model) to eliminate the steady-state error.

Chapter 8:

- Implementation of control schemes developed with the non-linear model of the launcher modeled by means of ASTOS;
- Analysis of control schemes based on non-linear model - rigid body;
- Robustness analysis of control schemes based on non-linear model - rigid body;
- Disturbance response analysis of control systems tested on a non-linear rigid body

model;

- Analysis of control schemes based on non-linear model - flexible body.

Future work

Given that during the thesis the moment of flight until the detachment of the first stage was studied, the three configurations of adaptive control systems will be applied and analyzed on the other portions of the trajectory. Also, the complexity of the tested case can be increased by adding atmospheric, aerodynamic, wind, etc. models. more detailed or with data taken from real missions of the launcher.

Also, the launcher reference mission can be extended to create a common design framework for the entire VEGA mission set.

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