Comparative Analysis of Flight Control Systems for Launching Vehicles

Carmen-Ioana BOGLIȘ, Anca BELEGA, and Andra NEGRU

Abstract—**The current paper is concerned with the rigid body dynamics and the stabilization of an unstable launch vehicle. In atmospheric flight, parameters linked to trajectory suffer variations, so a PD controller is designed based on the vehicle dynamics to achieve adequate stability and tracking performance.**

Index Terms—**attitude control, launch vehicle dynamics, PD controller.**

I. Introduction

A launch vehicle is a complex engineering structure that provides the speed necessary for the payload to exit Earth's gravity and place it on the orbit. It is made up of structural components and subsystems that are stably stored for long periods of time and must operate accurately at the time of launch [1]. Launchers were used to send human-made spaceships, unmanned spacecraft, and space satellites. Soyuz and Proton launchers in Russia, the Ariane series of Europe, the family of Atlas, Delta, and Titan vehicles in the United States are some examples [2].

As launchers are inherently unstable during atmospheric flight, the control system plays an important role in delivery missions as it influences both the performance and operations of the launch vehicle. During the climb, it is necessary to command a pre-determined trajectory, thus ensuring the necessary payload in orbit using the minimum amount of fuel. The problems related to the vehicle control are due to the fact that launch vehicles must be treated as flexible structures. Similar to flexible aircraft, the resulting dynamics is strongly coupled with significant interactions between rigid body dynamics and structural modes [3]. The forces acting on the launch vehicle resulting from atmospheric disturbance or active control of the vehicle excite the structure and cause the body to bend.

The basic purpose of the flight control system in an aerospace launch vehicle is to maintain the attitude of the vehicle commanded by the guiding section. The control system determines the attitude of the vehicle by means of an inertial measurement unit (IMU) and controls the corresponding change in the engine thrust vector to achieve the commanded attitude from the guidance section. The design of this system must meet three main, often contradictory requirements: stabilizing the vehicle, providing an adequate response to the steering controls and minimizing the angle of attack in the high dynamic pressure zone to ensure the structural integrity of the vehicle [4].

Several approaches on the design of the launch vehicle attitude control system can be found, such as [5-8].

The aim of this paper is to give a comparison between two control commands such as a PD controller and a state-feedback control.

II. Launch Vehicle Modelling

The rocket movement in the air is a complex phenomenon, influenced by the gravitational attraction, the action of the aerodynamic forces and couples, the rotation of the Earth, the variation of the meteorological parameters with the altitude and other factors. The flight can be divided into two main phases: atmospheric and exo-atmospheric flight (where the atmospheric forces can be neglected). The limit of these two is not well established, being about 120 km. As the performance of the launch vehicle is influenced by its environment, it is necessary to model the atmosphere (temperature, pressure and density) with precise approximations. Many atmospheric models have already been developed to meet the needs of launching vehicles and analysis of their trajectory [9].

For a preliminary analysis, the launching vehicle is considered to be completely rigid. This means that it does not change under the action of applied forces, simplifying the analysis by reducing the parameters that describe the system configuration in the case of rotation and translation. Assuming the hypothesis that the longitudinal axis of the rocket body is along the mass center of gravity, tangent to the trajectory, the weight, drag, thrust and aerodynamic are the forces acting on the vehicle.

Considering θ the pitch attitude, $\dot{z}$ the lateral drift speed, α_ω the wind incidence, m the vehicle mass, v the launch vehicle velocity, T the thrust, D the drag, L_α the aerodynamic force acting on the centre of pressure, I_y the pitch moment of inertia, δ the gimbal deflection angle, the following motion equations of the vehicle can be obtained [10], taking into account Fig. 1:

$$\ddot{\theta} = a_6\alpha - k_1\delta \quad (1)$$

$$\ddot{z} = \frac{-L_\alpha}{m}\cdot\alpha - \frac{T}{m}\cdot\delta - \frac{T-D}{m}\cdot\theta \quad (2)$$

$$\alpha = \theta + \frac{\dot{z}}{V} - \alpha_\omega \quad (3)$$

where $a_6 = \frac{L_\alpha \cdot l_{GA}}{I_y}$, $k_1 = \frac{T\cdot l_{CG}}{I_y}$ and $L_\alpha = qSC_{N_\alpha}$.

C.-I. BOGLIȘ is with the Military Technical Academy "Ferdinand I" and University "Politehnica" of Bucharest, Faculty of Aerospace Engineering, Bucharest, Romania (e-mail: ioana.boglis@mta.ro).
A. BELEGA is with the University of Brasov, Brasov, Romania (e-mail:anca.daniel@yahoo.com).
A. NEGRU is with the Military Technical Academy "Ferdinand I", Bucharest, Romania e-mail:andra.negru@mta.ro

Digital Object Identifier 10.32754/JMT.2019.1.08

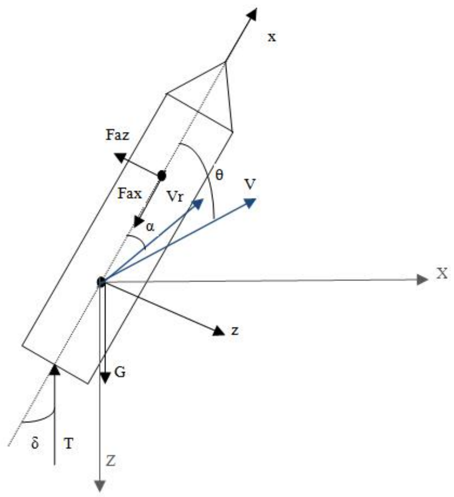


Figure 1. Simplified pitch-axis model of a launch vehicle

The equations above can be rewritten in state space form as follows:

$$\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\\ \ddot{z}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ a_6 & 0 & \frac{a_6}{v}\\ -a_1 & 0 & -a_2\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\\ \dot{z}\end{bmatrix}+\begin{bmatrix}0 & 0\\ a_6 & -k_1\\ a_2\cdot V & -a_3\end{bmatrix}\begin{bmatrix}\alpha_\omega\\ \delta\end{bmatrix}$$
$$\begin{bmatrix}\theta\\ \dot{\theta}\\ \dot{z}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\\ \dot{z}\end{bmatrix}+\begin{bmatrix}0 & 0\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}\alpha_\omega\\ \delta\end{bmatrix} \tag{4}$$

where $a_1=\frac{L_\alpha+T-D}{m}$, $a_2=\frac{L_\alpha}{mU}$ and $a_3=\frac{T}{m}$.

III. PD Control Design Method

For design purposes, a simplified rigid body model of Vega launch vehicle is used. VEGA is a light launcher designed to lift small payloads in Low Earth Orbit (LEO). Vega is designed as a single-body vehicle composed of three solid-propulsion stages, an additional liquid-propulsion upper module, and fairing for payload protection. Its four stages are controlled via thrust vectoring system (TVC) [11].

Taking its complete rigid model and neglecting the bending modes and its filters, the closed loop which is used on controller design is presented in Fig. 2.

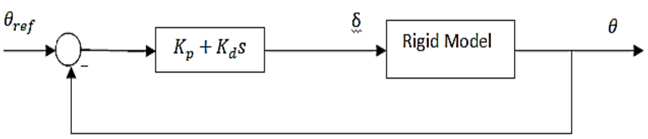


Figure 2. Block diagram of PD Architecture

The simulations will be considered for a worst case scenario such as the high dynamic pressure region (at time $t=56\,s$) and all the parameters are considered as time invariant.

The aim of using PD controller is to increase the stability of the system by improving control since it has an ability to predict the future error of the system response. Derivative action is usually used to improve transient response of the closed loop system. Only D control is not used because it amplifies high frequency noise which is never desired. Derivative action decreases rise time and oscillations [12].

The control command from the PD controller is:

$$\delta=-\begin{bmatrix}K_p & K_d\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\end{bmatrix}+K_p\theta_{ref}\,. \tag{5}$$

With the controller, the transfer function of the system in closed-loop becomes [5]:

$$\frac{\theta(s)}{\delta(s)}=\frac{\left(-K_p-K_ds\right)\left(a_3\cdot a_6/v+a_2k_1+k_1s\right)}{s^3+A_2s^2+A_1s+A_0}, \tag{6}$$

where $A_2=a_2-k_1K_d$, $A_1=-k_1K_p-a_2k_1K_d-a_6-a_3\cdot a_6\cdot K_d/v$ and $A_0=a_1\cdot a_6/v-a_2a_6-a_3\cdot a_6\cdot K_p/v-a_2k_1K_p$.

Using Ziegler-Nichols Tuning Method, the obtained values for the PD controller will be: $K_p=7.065$ and $K_d=1.1$. The system's answer to a step command shows very good response (shown in Fig. 3; for this time the wind will not be considered). Considering Vega Launcher's bandwidth stability constraints [13], this method is not a valid one for the considered situation.

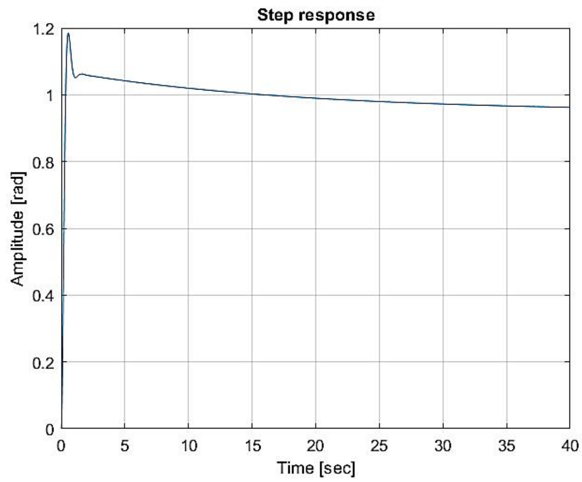


Figure 3. Controller's response for a step command

In order to tune the controller's coefficients, the trial and error method is used. The obtained values are: $K_p=7.25$ and $K_d=0.729$. The PD controller is evaluated with respect to the system stability margins and time domain response to a step command. The tracking performance of the controller and corresponding tracking error for a step command is shown in Fig. 4.

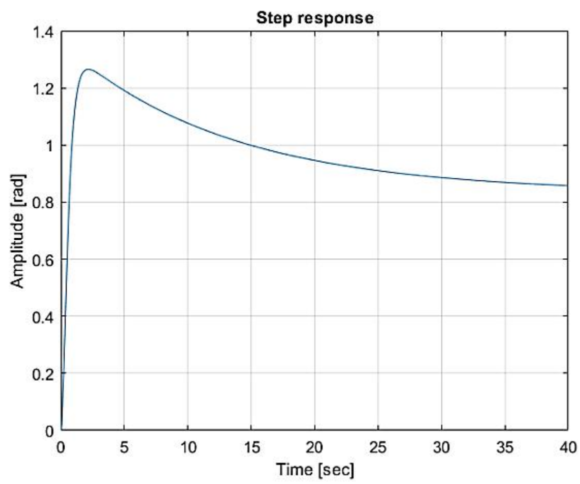


Figure 4. Controller's response for a step command

 Digital Object Identifier 10.32754/JMT.2019.1.08

The step response shows an acceptable overshoot of 0.21% and the final asymptotic value is 0.84 (for a step of 1) and the settling time is achieved at $t = 40$. The stability is guaranteed but the system has undesired performance.

The response for the PD controller, considering a disturbing angle of attack, $\alpha_\omega = 0.1256$ rad shows very small difference (as seen in Fig. 5).

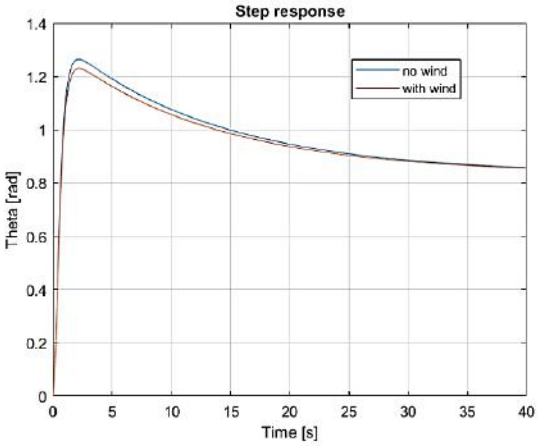


Figure 5. Controller's response to a step command and wind input

Considering a reference signal $\theta_{ref} = 0.03$ rad, the response of the system, having no wind input is shown in Fig. 6. The settling time is at $t = 58$ s and it shows overshoot of 2.5%.

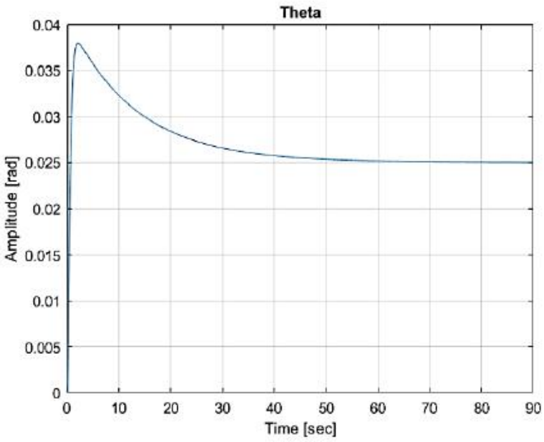


Figure 6. Theta response

Considering the wind input, response shown in Fig. 7, the system has/is over-damping and increases the rise time from approximately 1 s to 18 s.

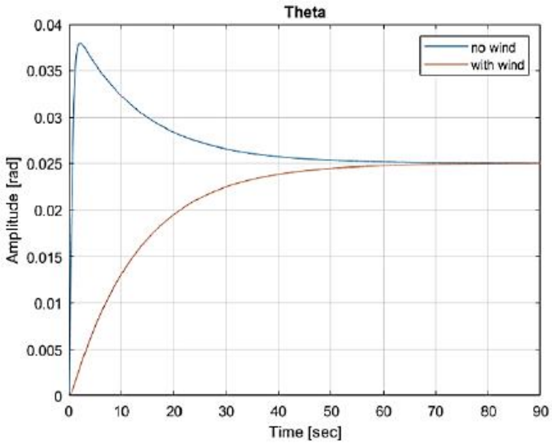


Figure 7. Theta response

In both situations, the system is characterized by a steady-state error of approximately 0.005 rad.

IV. State-Feedback Control Design Method

In the second case, a state-feedback control is used, with the following control law [14]:

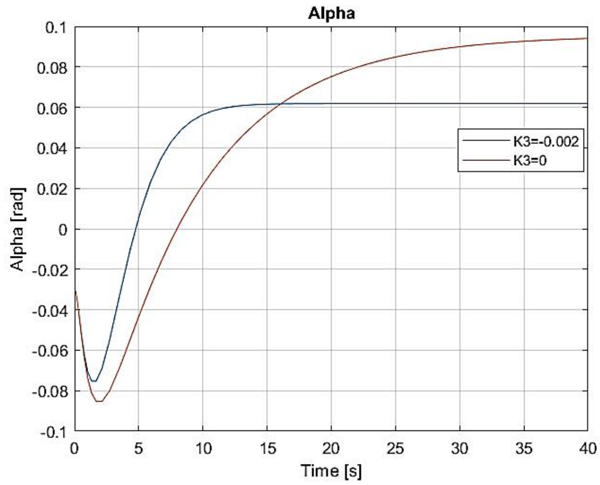
$$\delta(t) = K_1\theta(t) + K_2\dot{\theta}(t) + K_3\dot{z}(t). \tag{7}$$

Considering this, (4) becomes:

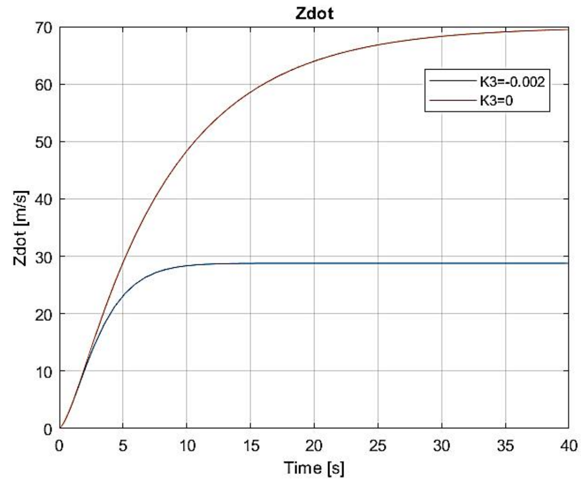
$$\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\\ \ddot{z}\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ a_6 - k_1K_1 & -k_1K_2 & \frac{a_6}{v} - k_1K_3 \\ -a_1 - a_3K_1 & -a_3K_2 & -a_2 - a_3K_3 \end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\\ \dot{z}\end{bmatrix} + \begin{bmatrix}0\\ -a_6\\ a_2V\end{bmatrix}\alpha_\omega \tag{8}$$

where the angle of attack, $\alpha(t) = \theta(t) + \frac{\dot{z}(t)}{V} - \alpha_\omega(t)$ and $K_1 = 1.05,\ K_2 = 0.7,\ K_3 = -0.002$.

Considering the input $\theta_{ref} = 0$ and $\alpha_\omega = 0.1256$ rad, the system shows that the steady state value of the angle of attack is zero (Fig. 8 a) and the steady state value of the velocity drift is the same as the wind velocity (Fig. 8 b).



a)

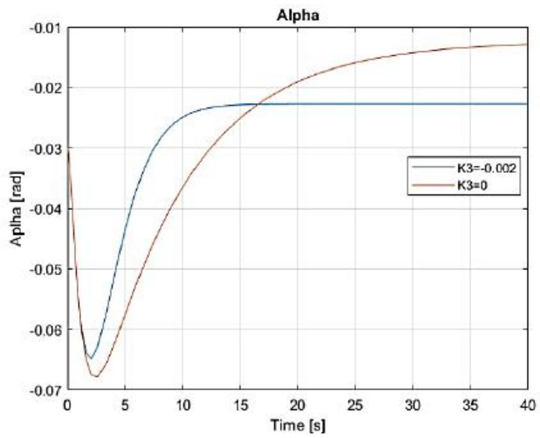


b)

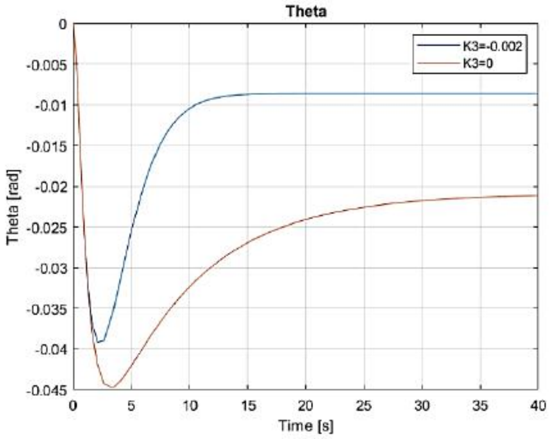
Figure 8. a) Alpha time response, b) Drift velocity time response

When the input $\theta_{ref} = 0.03$ rad is applied to the system, without the wind disturbances, the attitude is accurately tracked. When the drift velocity is induced, the tracking performance is deteriorated as can be seen in Fig. 9 a, 9 b and 9 c.

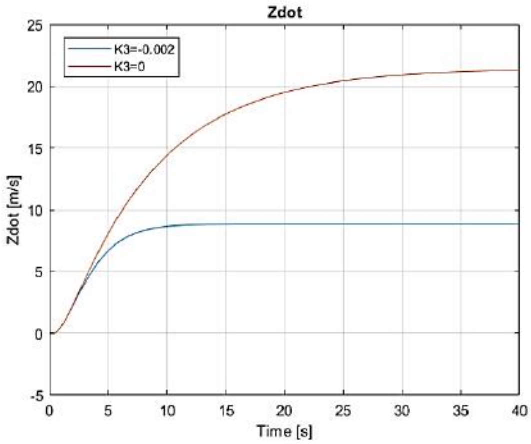
Digital Object Identifier 10.32754/JMT.2019.1.08



a)



b)



c)

Figure 9. a) Alpha time response, b) Theta time response, c) Drift velocity time response

V. CONCLUSION

This paper considered a PD controller and a state-feedback control to stabilize a closed loop unstable launch vehicle system during the atmospheric phase of the flight. It was shown that the PD controller can guarantee stability, giving good tracking performance. However, when introducing the wind and drift, the performance decreases, being necessary to introduce a new feedback. On the other hand, the state-feedback control can attenuate the wind disturbances, but deteriorates the tracking performance.

REFERENCES

[1] J. Hopkins Jr., J. Hopkins, and S. Isakowitz, *International Reference Guide to Space Launch Systems*, 4th ed., American Institute of Aeronautics & Astronautics, 2004.

[2] J. Anderson, *Fundamentals of Aerodynamics*, 6th ed., McGraw-Hill Education, New York, 2016.

[3] J. R. French, *Launch Vehicle Design*, Encyclopedia of Aerospace Engineering, 2010.

[4] N. Bletsos, “Launch Vehicle Guidance, Navigation, and Control,” Crosslink 5. pp. 30-33, 2004.

[5] E. Gadea Diaz, “Design of a robust controller for the VEGA TVC uing the µ-synthesis technique,” Master thesis, Noordwijk, 2011.

[6] B. Wie and W. Du, “Analysis and Design of Launch Vehicle Flight Control Systems,” AIAA 2008-6291, AIAA Guidance, Navigation, and Control Conference, August 2008.

[7] J. Orr and T. Van Zwieten, “Robust, Practical Adaptive Control for Launch Vehicles,” AIAA-2012-4549, August 2012.

[8] O. Voinot, P. Apkarian, and D. Alazard, “Gain-scheduling H∞ control of the launcher in atmospheric flight via linear parameter varying technique,” AIAAA Guidance, Navigation and Control Conference, Monterey, USA, 2002.

[9] D. M. Gaspar, “A Tool for Preliminary Design of Rockets”, master thesis, Lisbon, July 2014.

[10] A. Greensite, *Control Theory: Volume II - Analysis and Design of Space Vehicle Flight Control Systems*, London, UK: Spartan Books, Macmillan & Co. Ltd, 1970.

[11] *Vega User’s Manual*, Issue 3 Revision 0, A. b.

[12] A. Tewari, *Advanced Control of Aircraft, Spacecraft and Rockets*, Wiley, 2004.

[13] P. Simplicio, S. Bennani, A. Marcos, C. Roux, and X. Lefort, “Structured Singular-Value Analysis of the VEGA Launcher in Atmospheric Flight,” *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 6, pp. 1342-1355, 2016.

[14] A.-M. Stoica, C.-E. Constantinescu, “An H∞ State Feedback Control Law for Launch Vehicles,” ICMERA, 24-27 October 2014, Bucharest.