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Requirements for an Aerospace Actuation System derived from the Control Design Point of View

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Abstract. *This paper presents the assessment of performance and system requirements for a thrust vector control system (TVC). The TVC consists of a movable nozzle with a divergent and a flexible laminated bearing that is deflected by electrohydraulic actuators. The angular displacement of the nozzle results in thrust redirection, responsible for the attitude control of a launch vehicle. The system requirements of a TVC system for launch vehicles will be analyzed and discussed. Furthermore, ambiguous requirements found in the literature for the performance of the actuation system are pointed out. Finally, an integrated approach for obtaining TVC system requirements will be introduced, which leads to a balance between the control engineering side and the hardware side. This interaction between the different technical areas might anticipate problems and avoid requirements that are not able to be complied. The launch vehicle is represented by a rigid body model with six degrees of freedom and subsequently the necessary hypotheses are introduced in order to simplify and to linearize such model. Hence, a controller for the actuators is introduced to the model. The approach is divided into six steps including disturbance analysis and the introduction of physical limitations like saturation in angle and velocity. In order to verify this approach, a simulation with data from the VLS-1 (acronym, in Portuguese, for Satellite Launcher Vehicle) is used.*

Keywords: *Thrust Vector Control, Launch Vehicle, Requirements, Attitude Control*

1. INTRODUCTION

The mission of a satellite launch vehicle defines its trajectory which is specified by the linear and angular velocities, varying over time. The reference trajectory acts as input for the attitude control system. This system has to be capable of performing the desired attitude of the vehicle and furthermore it has be able to maintain control during disturbances. The main disturbances are caused by gust and shear wind. Most launch vehicles generate the required forces and moments for the control capability through angular deflection of a movable nozzle of a thrust vector control system. The aim of this work is to investigate the dynamic performance (slew rate ω_{SR} and bandwidth B_w) of the actuators which deflect the nozzle. The developed method can be applied for preliminary design of actuation systems for new launch vehicles.
Ramos and Leite Filho (2007) give an upgrade and validation of a launch vehicle attitude controller and Leite Filho et al. (2005) developed a H_∞ analysis to attenuate the bending effects. Carrijo and Leite Filho (2013) presented an approach to calculate the maximum angular deflection of a movable nozzle. Barbosa et al. (2013) presented experimental dynamic system identification of an actuation system using a movable nozzle.
In Section 2 a calculation for the dynamic performance of actuation systems is introduced and is compared with data available in literature. The launch vehicle is modeled as a rigid body, which is subsequently simplified and linearized, neglecting bending modes and filters in Section 3. In Section 4 an approach for integrated performance parameter generation is proposed and exemplary applied to the VLS-1 (acronym, in Portuguese, for Satellite Launch Vehicle).

2. PERFORMANCE PARAMETERS OF ACTUATION SYSTEMS

In this section the main parameters of thrust vector actuation systems are identified. Furthermore, calculations of actuator performances are proposed and compared with the data available in literature.

The main parameters that are used to generate requirements for a TVC system are: omni-axis vector angle capability β_{max} in [°], slew rate ω_{SR} in [°/s]), bandwidth B_w in frequency [Hz], duty cycle D in [°], operational time: T_{op} in [s], stability, steady state error (SSE) in [%], percentage overshot of commanded signal (PO) in [%] and the geometrical assembly and flexible joint torque moment.

In Fig. 1 an actuator working envelope is introduced. The upper limit of the working envelope is the physical limitation of the maximum vector angle capability β_{max}. The limitation of the frequency $f(\beta)$ can be calculated by the sinusoidal periodic excitation with the amplitude $A(t)$, the actuators bandwidth B_w and the slew rate of the actuator ω_{SR}.

$$A(t) = \beta_{max} \cdot sin(2\pi \cdot B_w \cdot t) \tag{1}$$

$$\omega_{SR} = max\left(\frac{dA}{dt}\right) = \beta_{max} \cdot 2\pi \cdot B_w \tag{2}$$

$$f(\beta) = \frac{\omega_{SR}}{2\pi \cdot \beta} \tag{3}$$

All TVC systems found in literature are included in Fig. 1 using the respective data (Tab. 1) for generation of the working envelope. The concept of an actuator working envelope is also used for the system requirements of the H-II TVC system in Ishibashi et al. (1995). The system requirements for Ariane 5 SRB, Castor 120, Vega Z23 and the M-3SII strap-on-booster do not provide such an envelope.
In the case of the Ariane 5 SRB, a vector angle capability of $\pm 5°$, a minimum vector slew rate of $15°/s$ and a bandwidth $B_w = 10Hz$ are given as system requirements (Caye and Descamps (1994)). However, this leads to ambiguity, since the maximum vector angle deflection ic not reached with 10 Hz. According to Eq. (3) the bandwidth with β_{max} would be $B_w \approx 0.48Hz$ instead of $10Hz$. An important parameter, the vector angle deflection β that corresponds to a bandwidth of $10Hz$ is missing.
Similar to the case of Ariane 5 SRB, Lee and Olsen (1993) defined the system requirements for the Castor 120 as following: vector angle capability of $\pm 5°$, minimum vector slew rate of $20°/s$ and minimum bandwidth of $3Hz$. The actuator is not able to respond a vector angle deflection of $\beta = \pm 5°$ with 3 Hz. The required slew rate with a given $B_w = 3Hz$ according to Eq. (2) would be $\omega_{SR} \approx 94°/s$ instead of $20°/s$.
For the Vega Z23 TVC system, Vanthuyne (2009) defined a bandwidth of $8Hz$ and a slew rate of $15°/s$, not explicitly mentioning the corresponding value of β. However, Carnevale and Resta (2007) defined the pass/fail criteria with an oscillation amplitude of $0.3°$. This corresponds to the bandwidth given in Vanthuyne (2009).
Akiba et al. (1983) defined the requirements for the TVC system of the strap-on-boosters of M-3SII launch vehicle consistent with vector angle capability of $\pm 3°$, maximum angular velocity of $13°/s$ and a duty cycle of $\pm 1.5°$ at 1.5 Hz for 40 s.

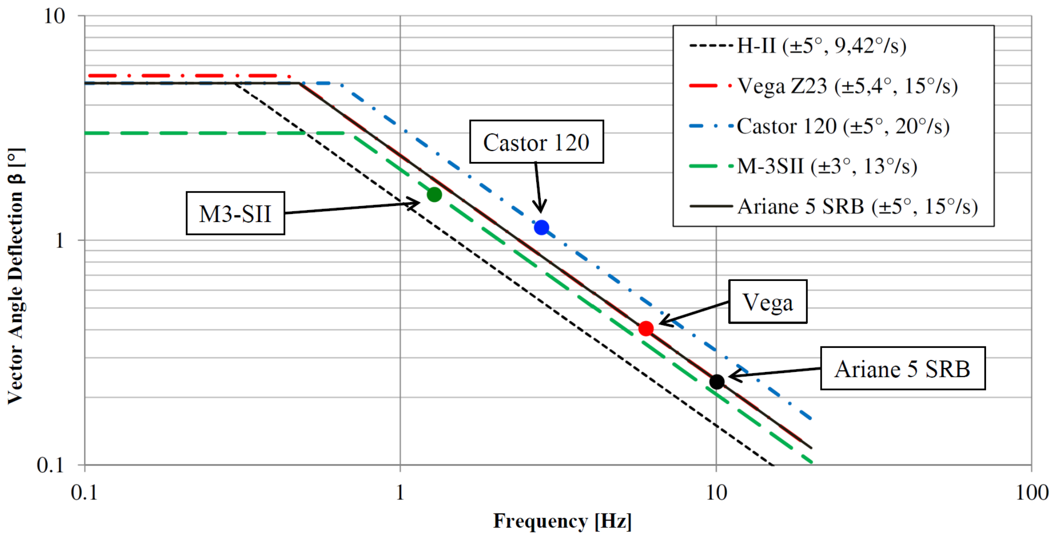

Figure 1. Actuator limitation caused by limited slew rate

In order to compare the performance of the different TVC systems, one definition of the design point D_P for all systems is established: The design point is that point on the edge of the working envelope where the maximum frequency with the maximum specified vector angle β_{max} coincide. It can be calculated by

$$D_P = \frac{\omega_{SR}}{2\pi \cdot \beta_{max}} \tag{4}$$

The design points for all available systems is calculated and listed in Tab. 1.

Table 1. Performance parameters of different TVC systems

Launch Vehicle	β_{max}	ω_{SR}	B_w	D_P
H-II	$\pm5°$	$9.42°/s$	N/A	0.30 Hz at $\pm5°$
Ariane 5 SRB	$\pm5°$	$15°/s$	10 Hz at $\pm0.1°$	0.48 Hz at $\pm5°$
Castor 120	$\pm5°$	$20°/s$	3 Hz at $\pm1.1°$	0.64 Hz at $\pm5°$
Vega Z23	$\pm5.4°$	$15°/s$	8 Hz at $\pm0.3°$	0.44 Hz at $\pm5.4°$
M-3SII strap-on-booster	$\pm3°$	$13°/s$	N/A	0.69 Hz at $\pm3°$

3. MODELING OF LAUNCH VEHICLE CONTROL SYSTEM

In order to identify the required dynamic response of the actuator (slew rate and the bandwidth) a model of the entire vehicle is generated and simplified. Once the plant is modeled, a control system can be introduced.

3.1 Vehicle as rigid body

The dynamics of the launch vehicle is modeled as a rigid body in six degrees of freedom, represented by Eq. (5) to (10), where u, v, w are the translational displacements and p, q, r are the rotational displacements. The forces acting on the vehicle can be divided into the thrust force of the propulsion system F_T, the gravitational force F_G and the aerodynamic force F_A. I_{xx}, I_{yy} and I_{zz} represent the moments of inertia about x, y, z axes of the body. The moments acting on the launch vehicle include aerodynamic moments M_A, jet damping moments M_{AJ}, aerodynamic damping moments M_{AD} and control moments M_C.

$$\dot{u} = \frac{F_{Tx} + F_{Gx} + F_{Ax}}{m} + vr - wq \tag{5}$$

$$\dot{v} = \frac{F_{Ty} + F_{Gy} + F_{Ay}}{m} + wp - ur \tag{6}$$

$$\dot{w} = \frac{F_{Ty} + F_{Gy} + F_{Ay}}{m} + uq - vp \tag{7}$$

$$\dot{p} = \frac{M_{AD\phi}}{I_{xx}} - \frac{\dot{I}_{xx}p + (Izz - I_{yy})qr}{I_{xx}} \tag{8}$$

$$\dot{q} = \frac{M_{C\psi} + M_{A\psi} + M_{AJ\psi} + M_{AD\psi}}{I_{yy}} - \frac{\dot{I}_{yy}q + (I_{xx} - I_{zz})pr}{I_{yy}} \tag{9}$$

$$\dot{r} = \frac{M_{C\theta} + M_{A\theta} + M_{AJ\theta} + M_{AD\theta}}{I_{zz}} - \frac{\dot{I}_{zz}r + (I_{yy} - I_{xx})pq}{I_{zz}} \tag{10}$$

3.2 Simplification and linearization of plant

Equations (5) - (10) of the rigid body is simplified using the following five simplification assumptions, based on Moreira and Kienitz (1993):

1. *Longitudinal velocity u treated as parameter*
   For a given trajectory, the profile of the velocity is assumed to have satisfactory precision and further disturbances can be neglected. The outcome is that the Eq. (5) can be neglected.

2. *Roll control torque assumed to be sufficiently higher than all introduced roll moment effects*
   Consequently, the moment has to be included in Eq. (8) using $M_{C\phi} = F_\phi l_\phi \beta_X$ with the introduced force F_ϕ, the lever arm l_ϕ and the control command β_X.

3. *Angular velocity of roll is assumed to be null ($p \approx 0$)*
   The angular velocity of roll p couples the planes of pitch (w and r) and yaw (v and q). Assuming small angles for roll, the planes pitch and yaw are decoupled and thus can be studied separately.

4. *Longitudinal velocity u is assumed to be much larger than the components of the wind velocity ($u >> v_{wind}$)*
   This hypothesis is valid during flight with exception of the first phase *lift-off and vertical flight* where no pitch and yaw maneuver are planed. Consequently, the angles of attack can be simplified according to Eq. (11) and Eq. (12).

$$\alpha_y = arctan\left(\frac{v - v_{y,wind}}{u}\right) \approx \frac{v - v_{y,wind}}{u} \tag{11}$$

$$\alpha_z = arctan\left(\frac{w - v_{z,wind}}{u}\right) \approx \frac{w - v_{z,wind}}{u} \tag{12}$$

5. *Roll angle and yaw angle always keep small*
   This hypothesis permits small-angle approximation in order to simplify the trigonometric functions of the relation between angular velocities of the body and the reference system, resulting in Eq. (13).

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & sin(\psi) \\ 0 & sin(\phi) & cos(\phi)cos(\psi) \\ 0 & cos(\phi) & -sin(\phi)cos(\psi) \end{bmatrix} \begin{bmatrix} \frac{d\phi}{dt} \\ \frac{d\psi}{dt} \\ \frac{d\theta}{dt} \end{bmatrix} \tag{13}$$

   If $p, \phi, \psi \approx 0$, than $q \approx \dot{\theta}$, $r \approx \dot{\psi}$, $p \approx \dot{\phi}$ and $qr \approx 0$.

Assuming that the equations for pitch and yaw decoupled planes are equivalent, for the further considerations only the pitch plane is analyzed. The linearization is applied around one specific instant of time during the flight (in the current case the transonic region) for θ_0 with $\theta = \theta_0 + \Delta\theta$, $\dot{\theta} = \Delta\dot{\theta}$ and $sin(\theta_0 + \Delta\theta) \approx sin(\theta_0) + \Delta\theta cos(\theta_0)$.

It can be demonstrated that the five hypotheses above result in Eq. (14) and Eq. (15) for each plane (in this case the pitch plane). The mathematical equations can be represented with the graphical simulation tool SIMULINK^{TM} in the red dotted box in Fig. 2, where θ_{ref} and θ are reference and the actual pitch angles referred to the inertial frame and β_z is the vector angle of the nozzle. The coefficients Z_{α_z}, μ_{α_z} and μ_q are related to aerodynamic parameters and Z_{β_z} and μ_{β_z} represent coefficients related to the thrust, varying with the flight time.

$$\dot{w} = -Z_{\alpha_z}\frac{w - v_{z,wind}}{u} + Z_{\beta_z}\beta_z - gsin(\theta_0) - gcos(\theta_0) + u\dot{\theta} \tag{14}$$

$$\ddot{\theta} = -\mu_q\dot{\theta} + \mu_{\alpha_z}\frac{w - v_{z,wind}}{u} - \mu_{\beta_z}\beta_z \tag{15}$$

3.3 Modeling of Control System

The control system is composed of a PI controller with an additional angular velocity feedback. The bending modes of the vehicle are not considered in the model. In later design phases the dynamic system behavior of the actuator can be identified and included in the modeling of the system Barbosa et al. (2013). For optimization of the Single-input single-output system (SISO) a linear-quadratic regulator (LQR) algorithm is applied. K_p, K_i and K_d represent proportional, integral and derivative gains, which are interpolated for the flight time. In Fig. 2 the complete, simplified launch vehicle plant including the control system is illustrated. Note, for preliminary analysis of performance, the actuator is considered linear and may be represented as a simple gain.

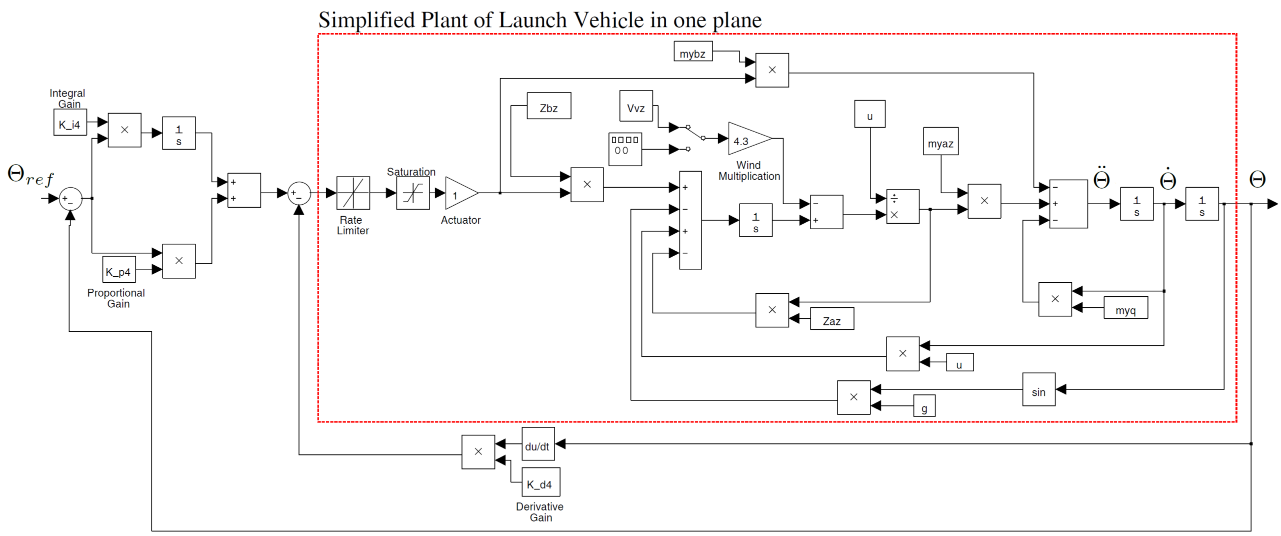

Figure 2. Closed loop model of the complete simplified launch vehicle plant including controller for one plane

4. APPROACH OF INTEGRATED PERFORMANCE PARAMETER GENERATION FOR TVC ACTUATION SYSTEM REQUIREMENTS

In this section an approach is proposed in order to obtain performance parameters for the actuation system necessary for stable control of the vehicle. This approach permits the inclusion of the physical and technological limitations of the hardware and the control algorithm for desired stable control. The following six steps are performed to generate parameters for performance requirements of a TVC, namely slew rate, bandwidth and the design point.

4.1 Modeling of control system without wind disturbance

The angular deflection is plotted over time in Fig. 3. Note, there are no disturbances of wind and the maximum angle deflection is approximately $0.4°$. In order to verify the stability of the control system, the reference signal θ_{ref} and command signal θ_{cmd} are plotted in Fig. 4.

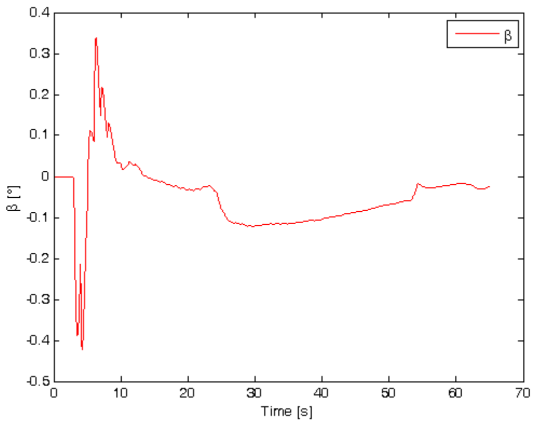

Figure 3. Angular displacement of nozzle over time without wind disturbances

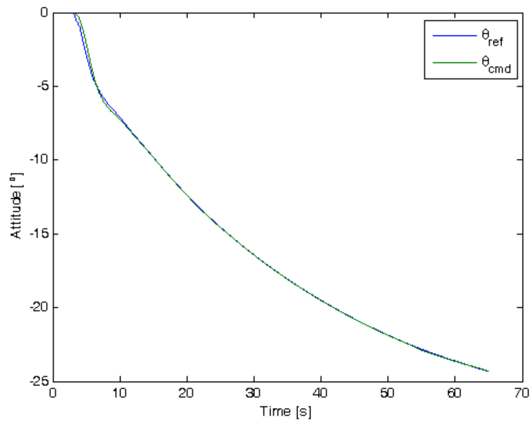

Figure 4. Reference and command signal without wind disturbances

4.2 Introduction of wind disturbance

Wind disturbances are introduced in order to verify the robustness of the system. The wind profile of a specific launch site is identified and included into the control loop. In Fig. 5 a synthetic wind profile for each plane, pitch and yaw, from the Alcantara Launch Site is taken (Moreira and Kienitz (1993)). For the following analysis only the pitch plane is taken into account.

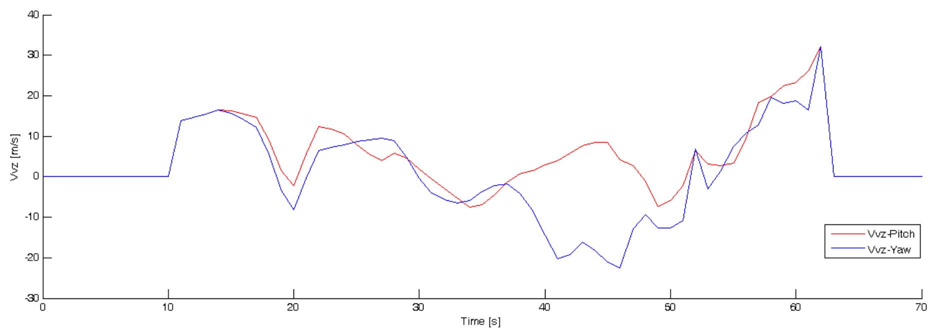

Figure 5. Wind profile for vehicle at Alcantara Launch Site Moreira and Kienitz (1993)

Figure 6 shows a maximum angular displacement of $\beta \approx 0.78°$, maintaining stability (Fig. 7).

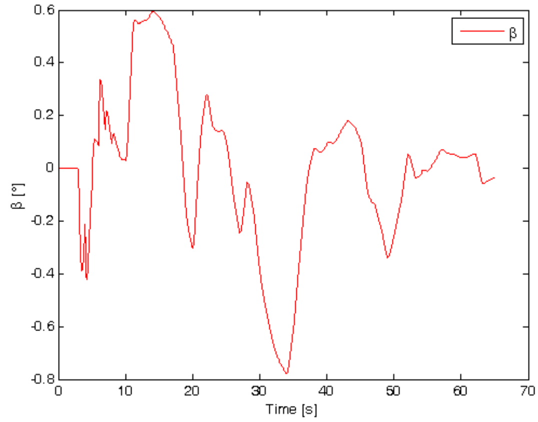

Figure 6. Angular displacement of nozzle over time with wind Vvz

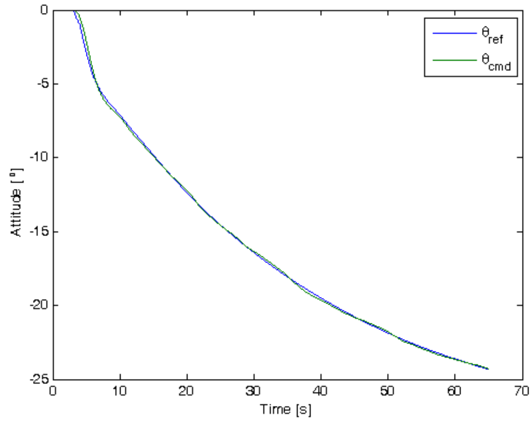

Figure 7. Reference and command signal with wind Vvz

4.3 Definition of maximum vector angle capability

The maximum vector angle capability β_{max} has to be defined. In case of VLS-1 the maximum used nozzle deflection was defined by $\beta_{max} = \pm 3°$. In the SIMULINK^{TM} model this can be achieved by introduction of a saturation (Fig. 2).

4.4 Introduction of a multiplying factor to the wind disturbance

The multiplying factor of the wind disturbance is introduced in the SIMULINK^{TM} model and manually adjusted to a value where β_{max} is obtained in one single point of the trajectory (Fig. 8). The value is identified to be 4.3. The command signal θ_{ref} is significantly oscillating around the reference signal (Fig. 9), however, maintaining stability.

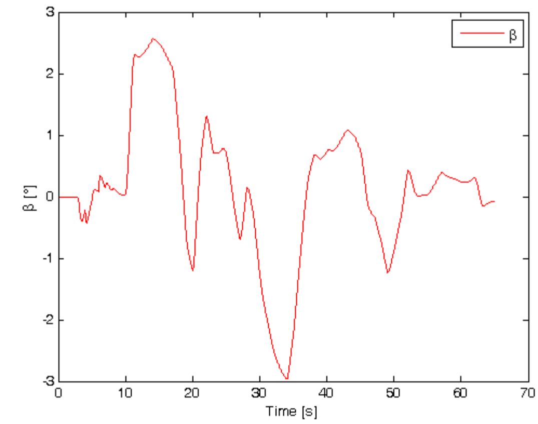

Figure 8. Angular displacement of nozzle over time with wind Vvz and a multiplying factor of 4.3

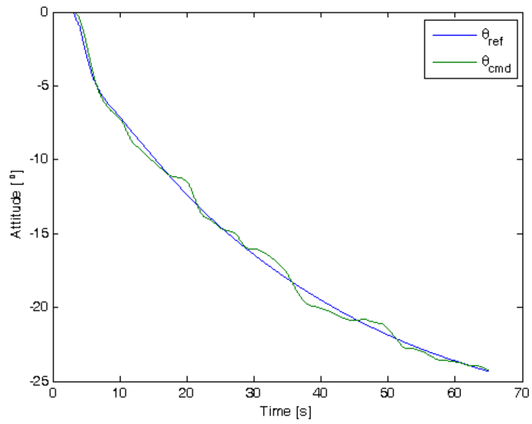

Figure 9. Reference and command signal with wind Vvz and a multiplying factor of 4.3

Further increase of the factor of wind disturbance leads to loss of control. The saturation of β_z limits the controllability (Fig. 10) and the vehicle deviates from the nominal trajectory (evident in Fig. 11).

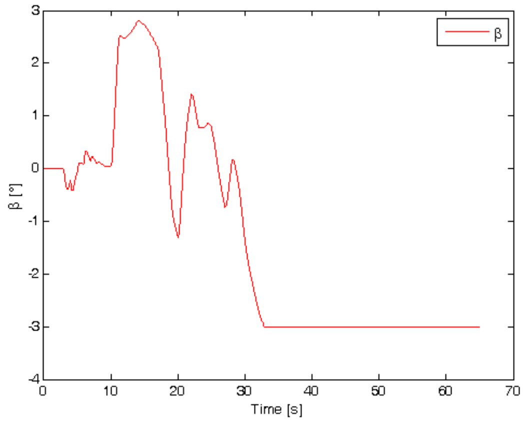

Figure 10. Angular displacement of nozzle over time with wind Vvz and a multiplying factor of 4.7

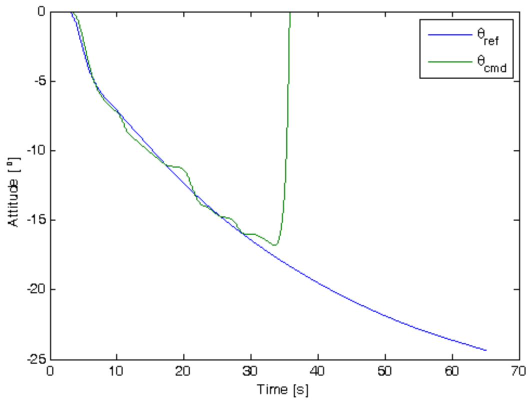

Figure 11. Reference and command signal with wind Vvz and a multiplying factor of 4.7

4.5 Derivation of β in order to obtain a minimum required slew rate

Using the wind disturbance multiplying factor of 4.3 for the given wind profile, the maximum vector angle capability of $\beta_{max} = 3°$ is obtained at one point of the trajectory. The curve β vs. time is then being differentiated in order to obtain a minimum required slew rate of $\omega_{SR} > 2.5°/s$, displayed in Fig. 12. In addition a rate limiter can be introduced, if the slew rate of a specific actuator or the slew rate of a specific technology is known.

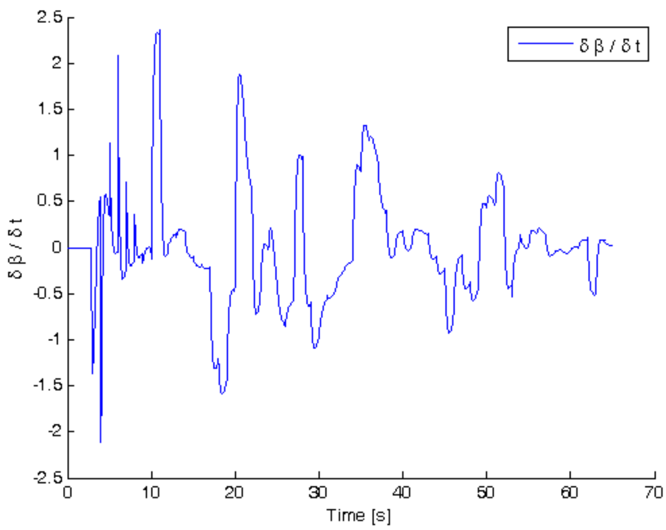

Figure 12. Minimum required slew rate of actuator

4.6 Calculation of minimum bandwidth and design point

According to Eq. (3) and (4) the design point can be calculated by the minimum bandwidth (Eq. 16), using the previous identified minimum slew rate.

$$D_P = B_{w,min} = \frac{\omega_{SR}}{2\pi\beta_{max}} = 0.13Hz \tag{16}$$

Note, the minimum bandwidth obtained from the approach is based on a rigid body model of the launch vehicle and thus, does not include the compensation of the natural frequency. Furthermore, uncertainty factors and a margin of safety should be considered.

5. CONCLUSION

Already in early design phases the quality of requirements is essential for the success of a project. Thus, in this work the system requirements for the actuation system of a TVC were defined in a first step. In a literature research ambiguous requirements in some cases, missing requirements/parameters in other cases were found. A calculation for performance parameters of the actuation system (slew rate ω_{SR} and bandwidth B_w) was presented and a common design point D_P was introduced in order to compare the dynamic performance of the different TVC systems.
For identification of the requirements for the dynamic performance of actuation systems, the launch vehicle was modeled using the approximation of a rigid body in six degrees of freedom. An approach of integrated performance parameter generation for TVC actuation system requirements was proposed and successfully applied to the Brazilian launch vehicle VLS-1. This approach can be applied in the preliminary design phase of future launch vehicle control systems. Future work will cover the implementation of bending mode compensation into the model.

6. REFERENCES

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