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Control law design for the Callisto demonstrator

Thomas Sivignon, James Caillaud**, and Jean Desmariaux+*
, ArianeGroup, 78310 Les Mureaux, France*
thomas.sivignon@ariane.group
james.caillaud@ariane.group
+ CNES, Launchers Directorate, 75012 Paris, France
jean.desmariaux@cnes.fr

Abstract
CALLISTO is an innovative project jointly led by CNES, JAXA and DLR with the objective to demonstrate the reusability of a small scale Vertical Take-off / Vertical Landing rocket. The control is performed through different kinds of actuators depending on the flight phase, including a gimballed engine with thrust modulation, a Reaction Control System (RCS) with 4 thrusters and 4 deployable fins. Two full scale missions are investigated: a so-called “Power Tilt-Over” (PTO) trajectory targeting a landing site close to the launch pad and including a return boost maneuver after the ascending phase, and a so-called “Down Range” (DR) trajectory targeting an off-shore landing platform. The wide range of flight conditions from take-off to landing and the targeted maneuvers lead to a vehicle that may be unsteady and nonlinear. At this stage of the project, ArianeGroup is in charge of designing the control law for the tilt-over maneuver, the back boost, the braking boost, the ballistic flight and the aerodynamic flight. This paper focuses on the studies carried out for the tilt-over maneuver. With high demands on agility and with a rate limited Thrust Vector Control (TVC), unstable pilot-induced oscillations (PIO) may occur during this phase. Based on a nonlinear frequential analysis and a temporal analysis, the effects of these oscillations and a solution to avoid them will be introduced.

1. Introduction

Launching a rocket into space, bring it back and launch it again seems to be a promising path to the cost reduction of space flights according to the new aerospace actors that are SpaceX and BlueOrigin. These companies have been developing reusable rockets since the mid 2000s usually called Vertical Take-off / Vertical Landing rockets. Such rockets raise several technical challenges. The vehicle which aspires to come back from space has to deal with a wide range of flight conditions. Dedicated actuation means, mission design and flight algorithms are required to efficiently keep it under control during the different flight phases leading to its recovery. With the objectives to raise the maturity of these technics and to assess the operational costs of a reusable stage, CNES, JAXA and DLR have jointly decided to design a Vertical Take-off / Vertical Landing demonstrator called “Callisto” [1].

In the context of this project, ArianeGroup is in charge of developing the control laws that will drive the vehicle during several flight phases including the tilt-over maneuver, the back boost, the ballistic flight, the braking boost and the glided aerodynamic flight. This paper gives an overview of the vehicle and the targeted missions and focuses then on the control during the slope tilt-over and the nonlinear topics that come with this maneuver.

2. The Callisto vehicle

Callisto is a small scale demonstrator of a launcher first stage and will perform recovery missions as representative as possible of a real operational launcher. The vehicle is around 13m height with a diameter around 1m. It is equipped with a gimballed main engine with reignition and thrust modulation capabilities developed by JAXA, a Reaction Control System (RCS) with 4 thrusters for the control during the ballistic flight and 4 deployable fins for the control

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during the aerodynamic flight. The landing phase may involve all the available control means, and relies on deployable legs which are unfolded shortly before the touchdown. The Figure 1 gives an illustration of the vehicle layout.

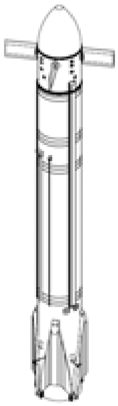

Figure 1: Callisto reference vehicle

Several tests will be conducted to validate the different subsystems before the main demonstrations. These full scale missions currently target two kinds of trajectories: one called “Power Tilt-Over” (PTO) which targets a landing site close to the launch pad, and another one called “Down Range” (DR) which targets an offshore landing site located at sea, ahead of the ascending trajectory. The first one is the most fuel consuming and the most technically constrained mainly due to the flight safeguard requirements. The DR mission requires designing a dedicated ship for the recovery, stabilization and return of the vehicle. Both scenarios are illustrated on the Figure 2.

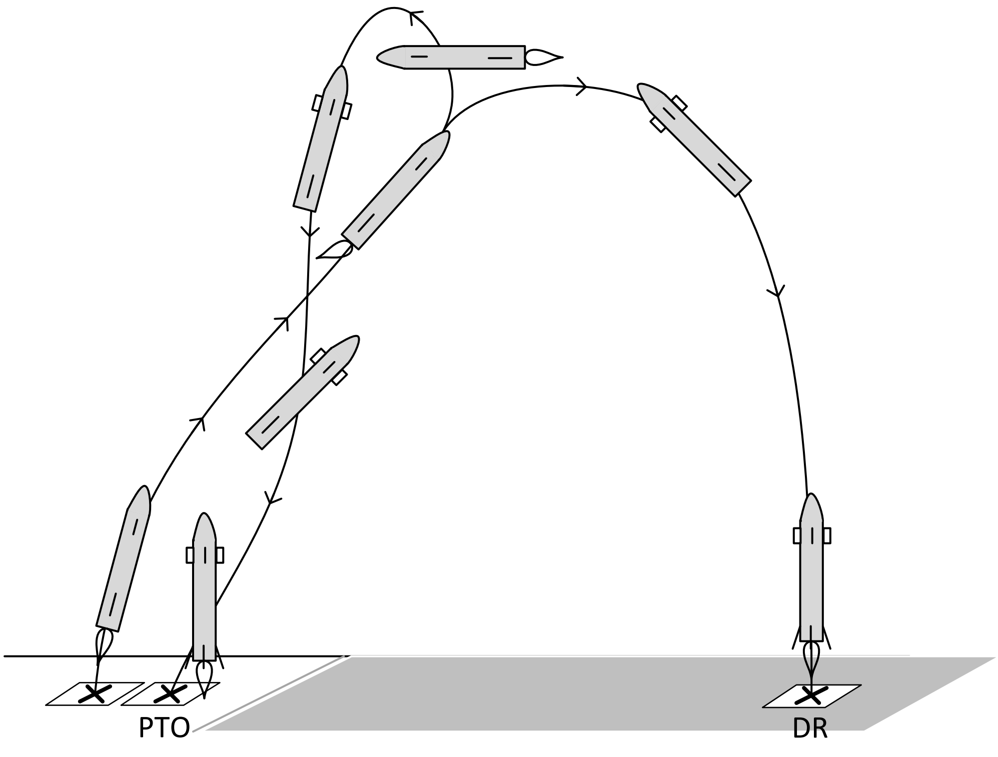

Figure 2: Illustration of the PTO and DR missions

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3. The PTO mission

Since the PTO trajectory is the most challenging in terms of control algorithms, the focus will be made on this mission. The different flight phases of the reference scenario will be briefly introduced in the following.

The reference PTO trajectory includes the following flight phases, as illustrated on Figure 3:
- take-off
- ascension
- slope tilt-over
- ballistic
- braking
- gliding
- landing

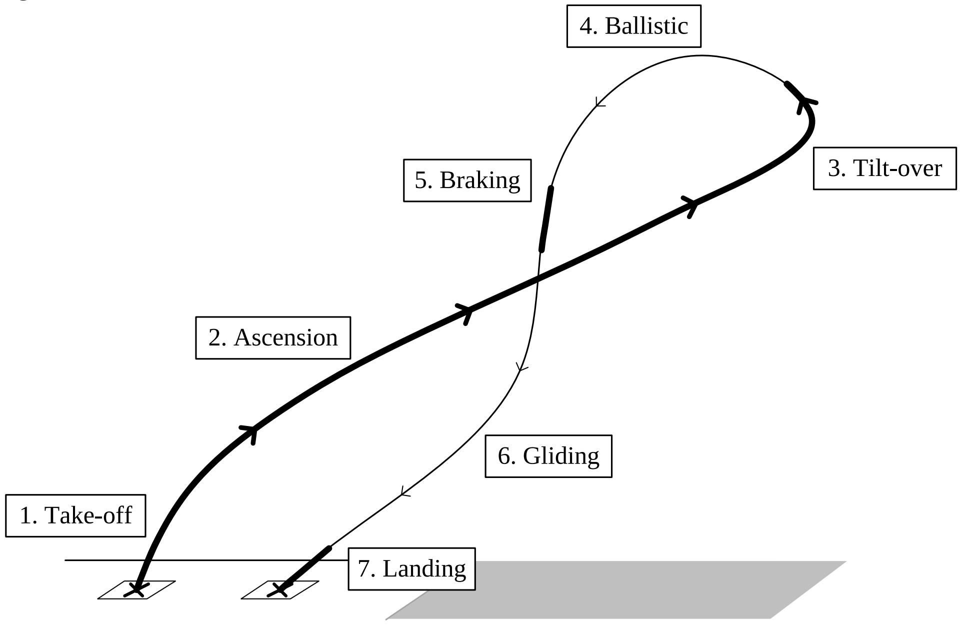

Figure 3: Flight phases of the reference PTO mission (powered phases in bold)

The take-off and ascending phases are close to classical take-off and ascension of an operational launcher. When the slope tilt-over is initiated, after the ascending phase, the vehicle has to direct the main engine thrust nearly perpendicularly to the vehicle speed to form the comeback trajectory. Doing this, the angle of attack (AoA) increases strongly and with a naturally instable vehicle it could lead to uncontrollable aerodynamic torques under high levels of dynamic pressure. This phase is therefore triggered once that the air density allows it. The tilt-over is realized by gimballing the thrust of the main engine. Once that the kinematic conditions are met, the main engine is cut off and the vehicle enters a ballistic phase; controlling its attitude through the RCS only. With a low dynamic pressure, this ballistic phase allows unfolding the fins. If necessary, a braking boost is provided at the beginning of the atmospheric reentry, ensuring a maximal Mach number before the setting of the aerodynamic loads. After this boost, the fins efficiency increases with the air density and the dynamic pressure. For safeguard purposes, under a failure of the fins deployment, the reference trajectory is designed so that the ballistic ending point following the braking boost is located at sea. Therefore the vehicle shall glide and actively modify its trajectory using the fins during the aerodynamic phase, in order to reach the desired landing site.

The tilt-over maneuver shall be performed as quickly as possible to limit the fuel consumption and the altitude of the culmination point of the trajectory. However, the performances of the vehicle are limited. In particular, the actuator is rate limited and may be saturated by the controller. Besides the reduction of the vehicle’s performances, these nonlinearities can destabilize it by introducing a loss of phase in the closed loop transfer. The following parts give an example of such a system, and then a simple solution is proposed to avoid the instability due rate saturations in actuator transfers.

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4. Control during a quick slope tilt-over

4.1 Solving the linear problem

Most of the controller synthesis methods used in the launcher industry are based on linear representations of the vehicles to control. Linear representations are easy to manipulate and allow using the simple and powerful design and analysis tools developed in linear control theory since the beginning of the 20th century. If the behavior of the vehicle is close to a linear system, the typical methodology is to find a linearization of the dynamics of the vehicle, then deploy the linear synthesis and analysis tools, and finally perform nonlinear temporal simulations to validate the hypotheses made during the linearization step. For instance, for a vehicle with a nonlinear actuator such as a saturated and rate limited Thrust Vector Control (TVC), the linearized representation considers an ideal linear TVC without saturation, eventually taking into account its dynamic linear transfer function. Temporal simulations are then achieved to demonstrate that the saturations are nearly never active or during very short amounts of time, such that a linear representation of the TVC is relevant.

Let's consider a simple linearized launcher dynamics, neglecting the aerodynamic effects:

$$\ddot{\theta} = K_1 \beta \tag{1}$$

where θ is its attitude angle, K_1 is the thrust deflection efficiency (linear relationship between the thrust deflection and the attitude acceleration) and β is the thrust deflection. This very simple system can be controlled using a classical proportional-derivative controller, denoted $[K_p\,;K_d]$ and synthetized such that the closed loop system has the desired 2nd order dynamics defined by a pulsation ω_0 and a damping coefficient ξ. The expression of the command gains is then simply given by identifying the characteristic equation of (1), giving:

$$K_p = \frac{\omega_0^2}{K_1}\,;K_d = \frac{2\xi\omega_0}{K_1} \tag{2}$$

The Figure 4 illustrates such a linear closed-loop system with θ_c the commanded attitude and θ the realized attitude, and Figure 5 gives an example of its temporal response, with arbitrary values of $K_1 = 5s^{-2}$, $\omega_0 = 3rd/s$ and $\xi = 0.7$.

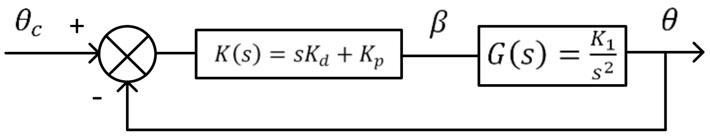

Figure 4: Closed loop representation of a simple linear launcher model during a tilt-over maneuver

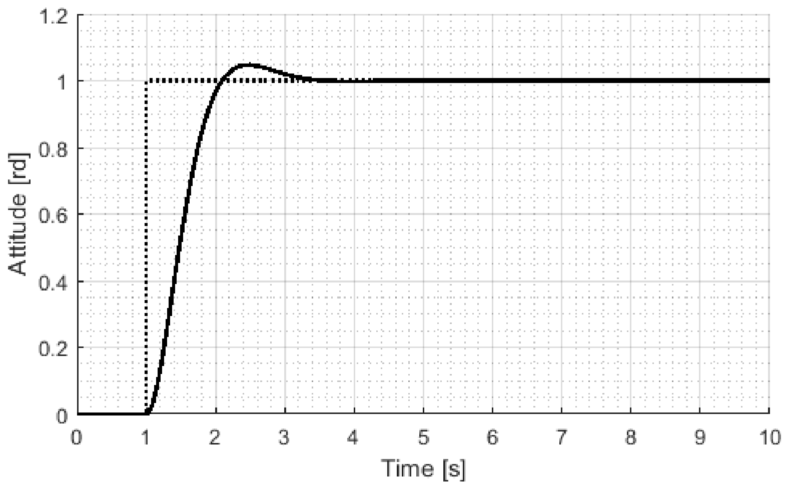

Figure 5: Response of the controlled linear system (solid) to a step command (dotted)

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4.2 Impact of a rate limited actuator

The requirement to perform the tilt-over maneuver as quickly as possible leads to choose high values for ω_0. Increasing ω_0 indeed increases the command gains. The resulting thrust deflection commanded to the TVC has then a faster dynamics with higher amplitudes, so that the maneuver duration is thus reduced with a linear TVC. Actually, the TVC might saturate if the command gains are too high, limiting the real performances of the controlled system. For control studies typically the TVC model can consider a linear dynamic transfer function in series with nonlinearities such as a rate limiter, a pure saturation, a dead zone and a bias. In this paper we will focus on a rate limited actuator, which can lead to unstable limit cycles if the controller dynamics is too fast, usually referred in the aeronautics as pilot induced oscillations (PIO).

Frequential analyses help revealing the existence of such oscillatory modes and require finding a linear representation of the rate limiter. Numerical simulations allow defining the response of nonlinear systems to sine waves of chosen amplitude in order to find a linear model. As a first approximation, this amplitude is set to the maximal expected value of the commanded deflection following a unitary step of commanded attitude. The following Bode diagrams illustrate the resulting linear models for several rate limits:

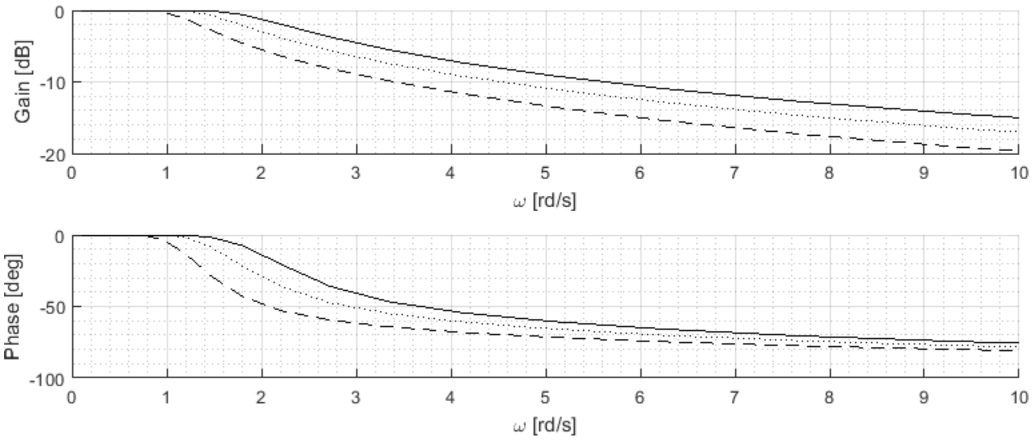

Figure 6: Linear estimation of rate limiters
(solid: 2.5rd/s, dotted: 2.0rd/s, dashed: 1.5rd/s)

Coupled with the linear system of Figure 4, the Black diagrams of the open loop transfer of the controlled system are given on Figure 7.

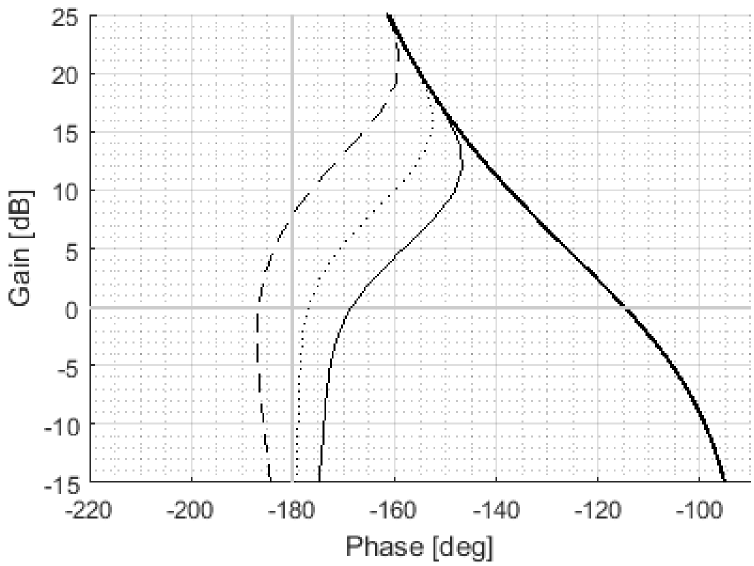

Figure 7: Controlled open loops with rate limited actuators
(bold: w/o rate limit, solid: 2.5rd/s, dotted: 2.0rd/s, dashed: 1.5rd/s)

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Figure 7 indicates that we can find a rate limit (around 2.0rd/s in this example) for which the closed loop will become unstable due to the phase shift of the nonlinearity. The Figure 8 gives temporal responses of nonlinear closed loop systems with several rate limits.

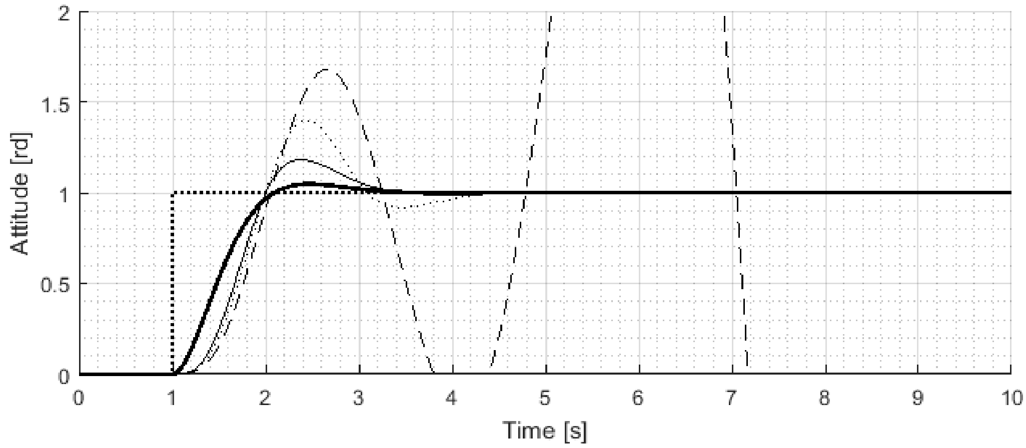

Figure 8: Temporal responses of nonlinear closed loop
(bold-dashed: command, bold: w/o RL, solid: 2.5rd/s, dotted: 2.0rd/s, dashed: 1.5rd/s)

4.3 Phase compensation of rate limited actuators

Rate limiters inside the actuator may introduce a strong phase shift in the global closed loop system until it becomes unstable. Several methods can be used to avoid exciting the limit cycles. One of the most wide spread solutions consist of filtering the commanded input, i.e. the commanded attitude in this example. Such solutions impact the temporal performances of the global controlled system, even while the actuator is operating in its linear domain. On the contrary, a nonlinear phase compensator will be introduced in the following. This solution, widely inspired from [2], extends the stability domain of the nonlinear closed loop system, with a limited cost on its temporal performances and is only effective when the TVC has a nonlinear behavior.

The phase compensator proposed here is a simple low frequency feedback on the error between the commanded deflection and the realized one, as illustrated on the Figure 9. Such implementations desaturate the actuator output upon a reversal of the high frequency signal.

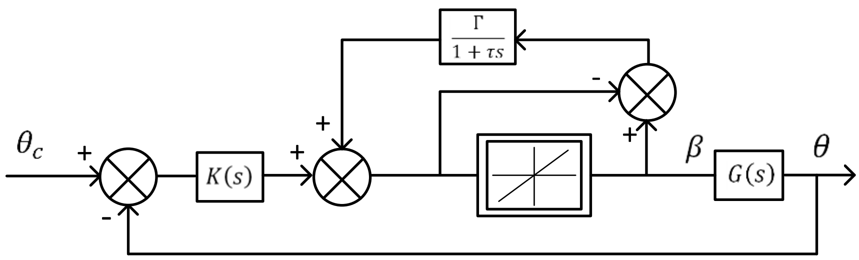

Figure 9: Closed loop with phase compensator

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Focusing on the example of a 1.5rd/s rate limiter, the Black diagram of the compensated controlled system is plotted on Figure 10 with the tuning $\Gamma = 1.5$, and $\tau = 0.2s$.

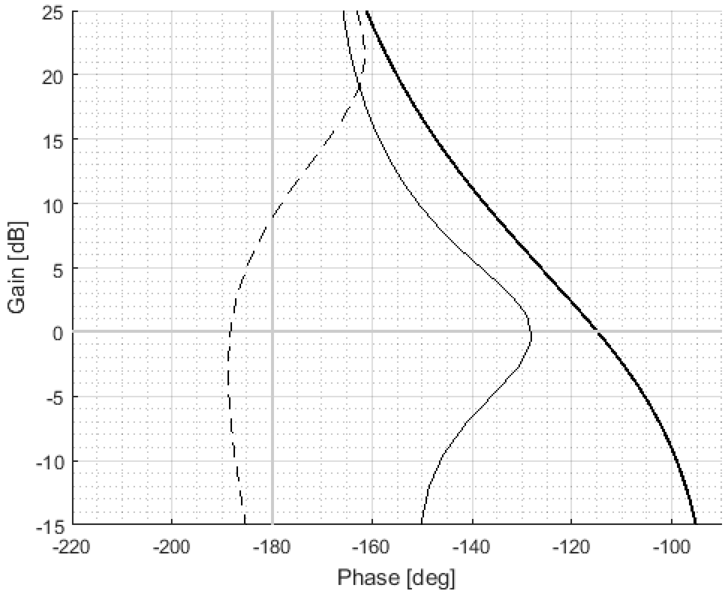

Figure 10: Comparison of the linear system (bold solid), the nonlinear system (dashed) and the nonlinear system with a phase compensator (solid)

The chosen tuning for the compensator only depends on the linearized TVC characteristics. Temporal simulations are given on Figure 11 and confirm that the stability of the compensated system is increased compared to the results of Figure 8.

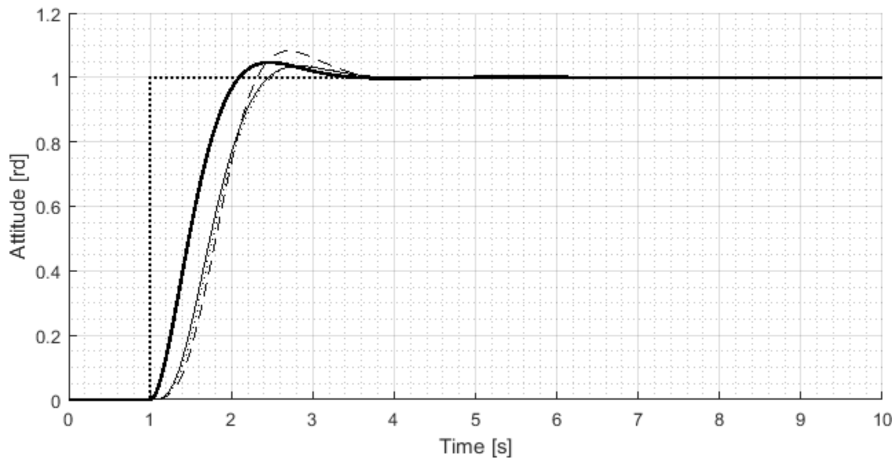

Figure 11: Temporal responses of nonlinear closed loop with a phase compensator (bold-dashed: command, bold: w/o RL, solid: 2.5rd/s, dotted: 2.0rd/s, dashed: 1.5rd/s)

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5. Conclusion

In this paper the Callisto project of a Vertical Take-off / Vertical Landing demonstrator has been introduced. This reusable rocket is jointly developed by CNES, JAXA and DLR to raise the maturity of the required technical knowledge, and to assess the operational costs of a reusable launcher first stage. Each targeted full scale mission for Callisto includes several flight phases which involve different kinds of actuating systems. For the PTO mission which targets a landing site close to the launch pad, a quick slope tilt-over is necessary at the end of the ascension. This maneuver requires high deflection dynamics and pilot induced oscillations might occur if the controller is too fast regarding the actuator performances. In particular, rate limiters inside the TVC were introduced, with an assessment of their impact on the controlled system stability. In order to increase the stability domain of such nonlinear controlled systems, a feedback-based phase compensator has been tested on an arbitrary launcher model. The results shows that this solution efficiently extends the stability domain of the nonlinear closed loop system with a very limited cost on the temporal performances compared to widely spread solutions such as filtering the command profiles.

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