Design of a robust controller for the VEGA TVC using the L1-Adaptive Control

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Abstract: *The purpose of this study is to Design of a robust controller for the VEGA TVC using the L1-Adaptive Control. The performance of the system with an L1 adaptive controller has been compared with that of a classical controller. The L1 adaptive controller optimization is an efficient as well as an effective approach for the design of a robust controller. The L1 adaptive controller ensures the robustness of the system against uncertainties, noise, and disturbances[10]. In a launch vehicle parameters like mass, thrust, and aerodynamic properties are time-varying. Due to the time-varying nature of these parameters gain scheduling is necessary with the classical control design methods otherwise the closed-loop system might become unstable for some values of these parameters. This procedure is costly and has no robustness. In addition to this, there are external disturbances also which can make the control system unstable. This is the reason why robust control is necessary. There is a trade-off between achievable performance and robustness. So, we need to compromise between required performance and robustness as per the requirement.*

Key Words: *Classical controller, L1 adaptive controller, Rigid body model, Robustness and Performance, Stability*

1. INTRODUCTION

VEGA launcher is the new European Small Launch Vehicle developed under the responsibility of the European Space Agency (ESA) and European Launch Vehicle (ELV/AVIO) as prime contractor. The launcher has successfully performed twelve launches since its maiden flight on 13 February 2012 [1]. VEGA is a single-body launcher, which follows a four-stage approach (see Figure 1.1) [2]. The key feature of L1 adaptive control architectures is the guaranteed robustness in the presence of fast adaptation [3]. With L1 adaptive control architectures, fast adaptation appears to be beneficial both for performance and robustness. At the same time, the trade-off between the two is resolved via the selection of the underlying filtering structure. The tracking error can be arbitrarily small during transient by increasing the adaptive gain. A high adaptive gain however makes the differential equation of the adaptive law or estimator very stiff and leads to numerical problems that cause high oscillations in the estimated parameters leading to loss of adaptivity and deviations from what the theoretical properties dictate. In [4], the underlying linear nonadaptive computable L_2- and L_∞-bounds for the output tracking error signals were obtained for a controller possessing a parametric robustness property. However, for a large parametric un- certainty it requires high-gain feedback**.** L1adaptive control can be viewed as a modified classical model through using the L1 adaptive theory equations [5]. High values of the adaptation gains are thus advantageous. Another feature [6]. Is that the control signal is filtered to avoid high frequencies in the control signals [7]. In this paper, the possibility of designing a strictly positive real adaptive control system for this system of the launch vehicle was analyzed. The interest in this class of systems is determined by the robustness properties of the stability of strictly positive real systems and some theoretical results demonstrated in [8]. The key feature of L1 adaptive control architectures is the guaranteed robustness in the presence of fast adaptation. With L1 adaptive control architectures, fast adaptation appears to be beneficial both for performance and robustness than the existing classical model, while the trade-off between the two is resolved via the selection of the underlying filtering structure. L1 adaptive control has been tested in several applications, most notably flight control for aircraft, missiles, and spacecraft. The flight tests cover control surface and sensor failures and other sources of unmodeled dynamics the [9] tracking error can be made arbitrarily small during transient by increasing the adaptive gain. A high adaptive gain however makes the differential equation of the adaptive law or estimator very stiff and leads to numerical problems that cause high oscillations in the estimated parameters leading to loss of adaptivity and deviations from what the theoretical properties dictate.

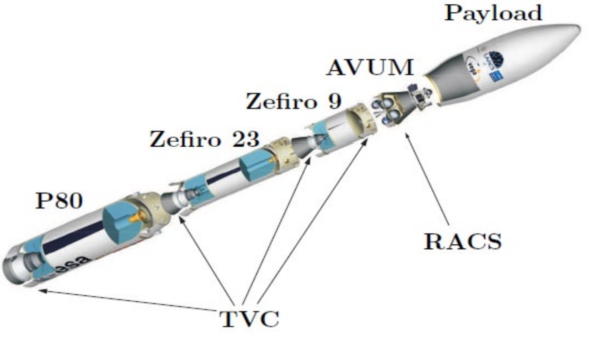


Fig. 1 - Structure of the Vega Launcher

2. PD CLASSICAL CONTROLLER

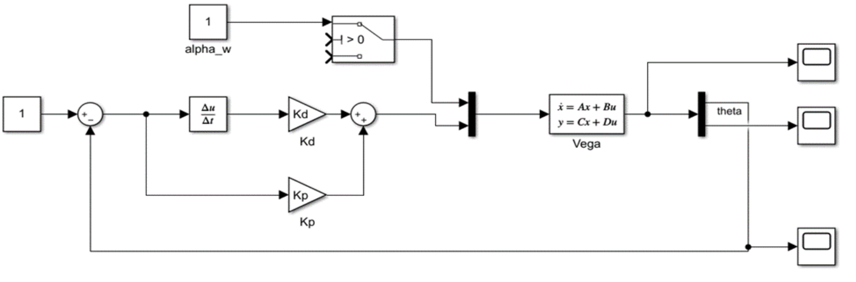


Fig. 2 - Block diagram of Complete Rigid body with K_d and K_pController and state space

A PD controller can guarantee stability and performance in at least a basic two states SISO model [4]. However, this model was built assuming that there was no drift and no wind so α =

θ but when introducing the drift and the wind $\left(\boldsymbol{\alpha} = \boldsymbol{\theta} + \frac{\mathbf{z}^{\cdot}}{\mathbf{V}} - \boldsymbol{\alpha}_{\boldsymbol{\omega}}\right)$ where $\boldsymbol{\alpha}_{\boldsymbol{\omega}}$ is the wind incidence, **V** is the LV velocity and $\mathbf{z}^{\cdot}$ is the lateral drift speed.

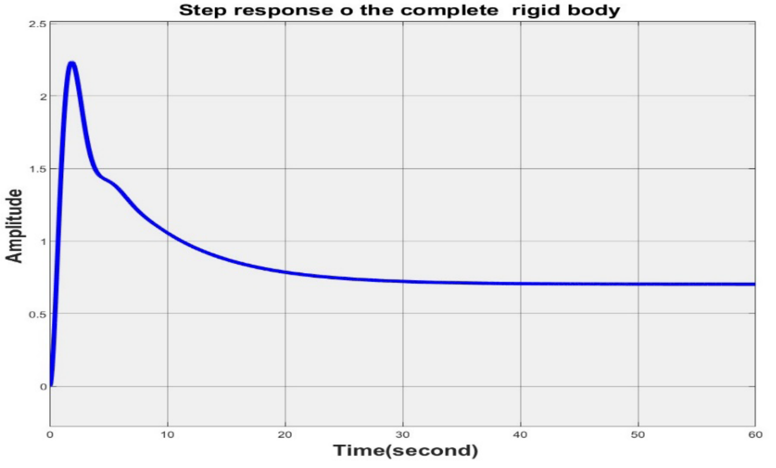


Fig. 3 - Step Response of the complete Rigid body model

3. L1 ADAPTIVE CONTROLLER

The advantages of the L1 adaptive controller are:
1. Guaranteed fast adaptation.
2. Decoupling between adaptation and robustness.
3. Guaranteed transient performance.
4. Not achieved via persistent excitation, control reconfiguration or gain-scheduling.
5. Guaranteed time-delay margin.
6. Performance limitations reduced to hardware limitations.
7. Suitable for development of theoretically justified verification and validation tolls for feedback systems and the uniform scaled transient response dependent on changes in:

- Initial condition.
- Value of the unknown parameter.
- Reference input.

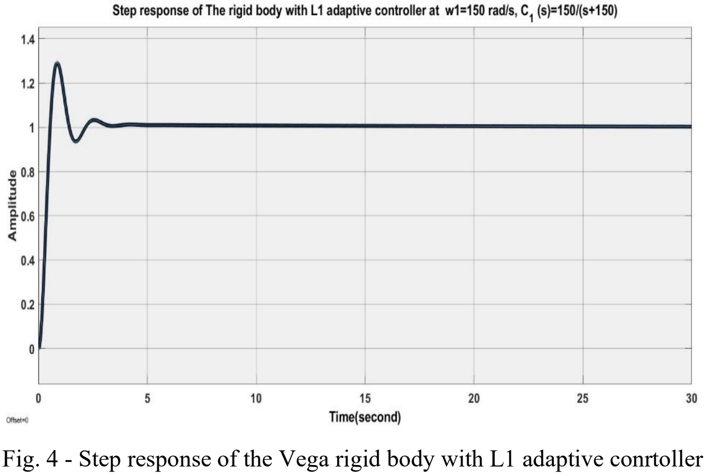


Fig. 4 - Step response of the Vega rigid body with L1 adaptive conrtoller

4. ROBUSTNESS OF THE RIGID BODY

The advantages of the weight functions are Mitigating the effects of flexible modes. Rejection of disturbances due to wind and gusts [10]. Ensuring robustness with respect to modeling uncertainties both in the case of the rigid model, as well as in the case of the presence of flexible modes [11].

The selection of weighting functions is the most important step in the robust controller design process, as they define the desired closed-loop behavior [12]. Since the performance objectives are mainly related to the sensitivity function, the weighting function must be designed to reflect the performance requirements.

For good tracking performance, the magnitude of the sensitivity function should be minimized. Since tracking performance and disturbance rejection are important at low frequencies, the sensitivity function S is minimized in this range. Proper selection of frequency-dependent weighting functions can result in smoothing the disturbance over a desired frequency range, as well as disabling the control action at high frequencies, where measurement noise and uncertainties can degrade control performance.

The performance of the system with an L1 adaptive controller has been compared with that of a classical controller [13]. The L1 adaptive controller optimization is an efficient as well as an effective approach for the design of a robust controller.

The L1 adaptive controller ensures the robustness of the system against uncertainties, noise, and disturbances. In a launch vehicle parameters like mass, thrust, and aerodynamic properties are time-varying.

Due to the time-varying nature of these parameters gain scheduling is necessary with the classical control design methods otherwise the closed-loop system might become unstable for some values of these parameters.

This procedure is costly and has no robustness. In addition to this, there are external disturbances also which can make the control system unstable. This is the reason why robust control is necessary.

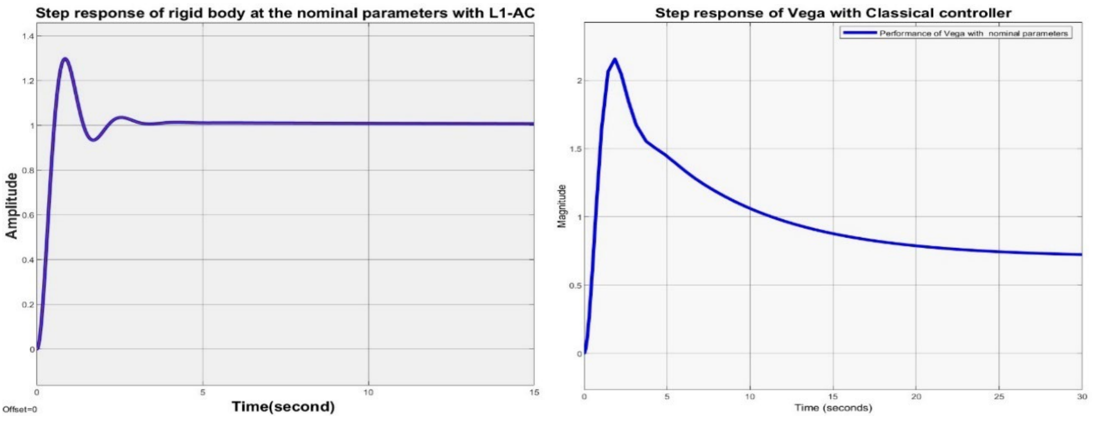
There is a trade-off between achievable performance and robustness. So, we need to compromise between required performance and robustness as per the requirement. Seven cases were defined at the time of the test scheme to consider the two uncertainty intervals for each uncertain parameter in Table 1 plus the nominal case.

The nominal case contains the nominal values of the parameters, considering an uncertainty interval of ± (10%,15%, and 20%) of their value and the nominal values of the parameters at the maximum dynamic pressure region.

Table 1. The uncertainty interval of the parameters of the Vega rigid body

Parameters	Nominal	Higher10%	Lower10%	Higher20%	Lower20%
a1	37.87	41.657	34.083	45.4440	30.2960
a2	0.02737	0.030107	0.024633	0.0328	0.0219
a3	25.54	28.094	22.986	30.6480	20.4320
a6	3.2297	3.55267	2.90673	3.8756	2.5838
K1	7.0738	7.78118	6.36642	8.4840	5.6560

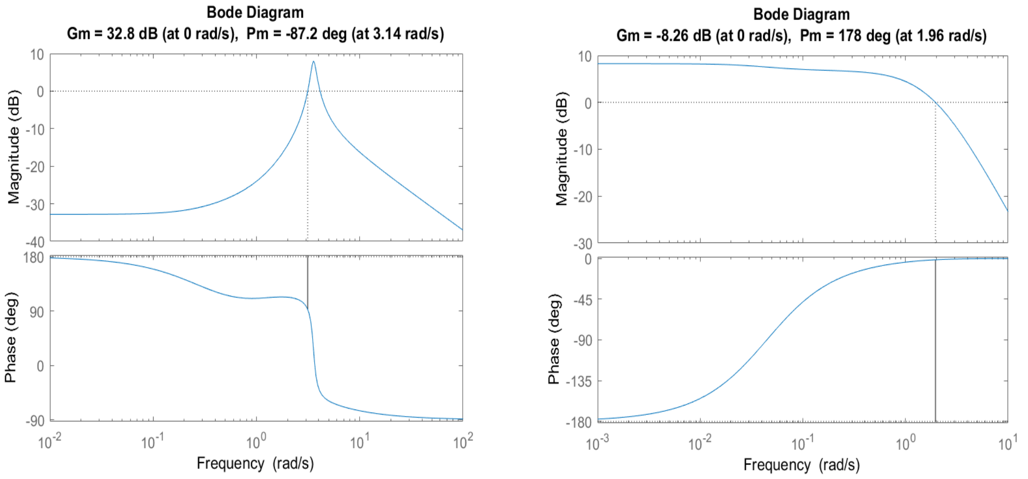
In the case 1. To know the path that the nominal parameters will behave it, we will use the values of these parameters to find the performance of the Vega rigid body, by the replacing the nominal parameters in case of the classical and L1 adaptive controller such as: $a_2 = 37.87$, $a_2 = 0.02737$, $a_3 = 25.54$, $a_6 = 3.2297$ and $k_1 = 7.0738$, and we find the step response and bode plot.



(a) Step response of the L1 adaptive controller (b) Step response of the classical controller

Fig. 5 - Step responses of L1 adaptive and classical controller of the Viga rigid body with nominal parameters

From (Fig. 1.b) The classical controller is unable to deal with this much amount of variation and the systemic becoming critically stable however system, but with the L1 adaptive controller in (Fig. 1.a) the system is stable and provides a good response and the overshoot of the step response of the L1 adaptive controller with the amplitude equal to 1.3db, with time equal to 2.5 seconds, while in classical controller the overshoot with amplitude equal to 2.5db, with time equal 5second.



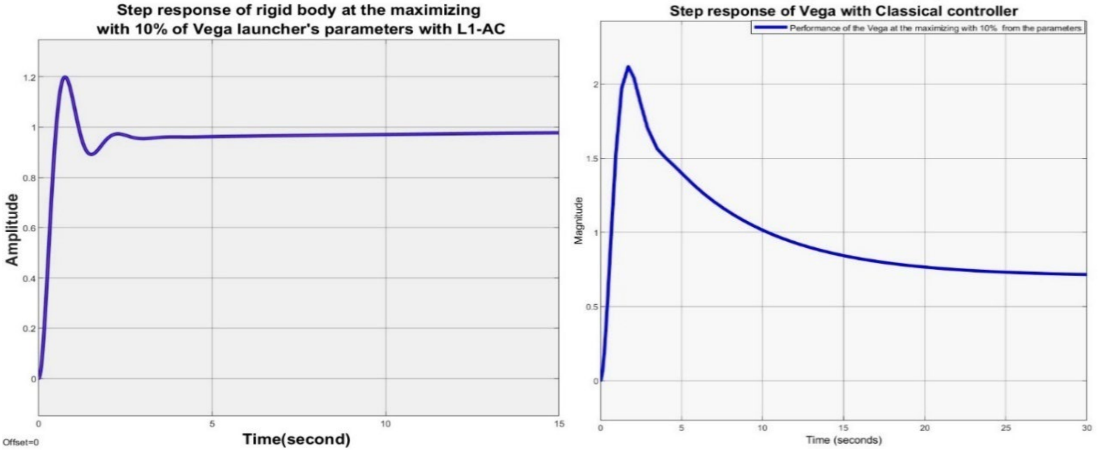
(a) Bode plot of the L1 adaptive controller (b) Bode plot of the classical controller

Fig. 6 - Bode plot of the L1 adaptive and the classical controller with nominal parameters

From (Fig. 2.a) The bode plots of the L1 adaptive controller provides better margins (gain margin = 32.8) and better eigenvalues as compared to the classical PD controller (gain margin = -8.26) in (Fig. 2.b) and bad eigenvalues.

The eigenvalues for the L1 adaptive controller	the eigenvalues of the classical controller
-0.8400 + 1.5389i	-1.8309
-0.8400 - 1.5389i	1.7625
-0.1448 + 0.0000i	0.0410

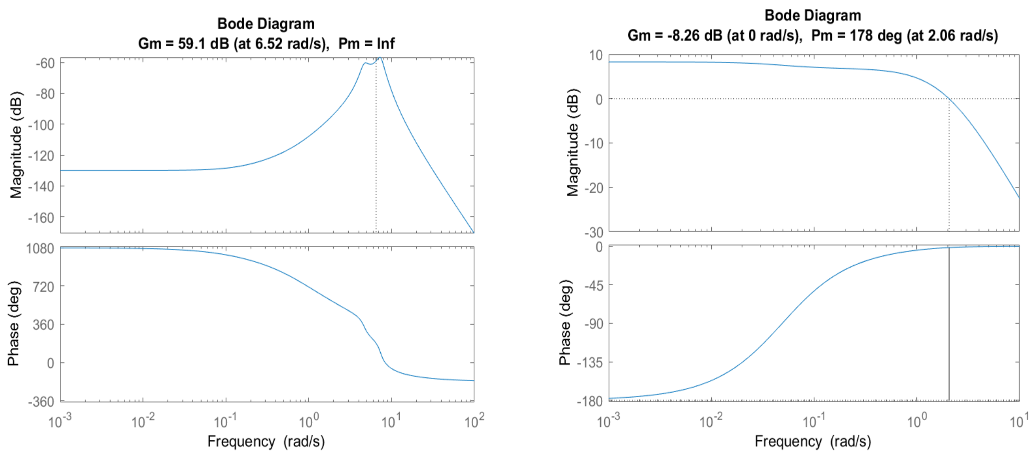
In case 2. We replacing the parameters with the maximizing with 10% in case of the classical and L1 adaptive controller such as: $a_1 = 41.657$, $a_2 = 0.030107$, $a_3 = 28.094$, $a_6 = 3.55267$ and $k_1 = 7.78118$.



(a) Step response of the L1 adaptive controller (b) Step response of the classical controller

Fig. 7 - Step responses of L1 adaptive and classical controller of rigid body with Maximizing 10% of parameters

From (Fig. 2.b) The classical controller is unable to deal with this much amount of variation and the systemic becoming critically stable however system, but with the L1 adaptive controller in (Fig. 2.a) the system is stable and very close to 1, and provides a good response and the overshoot of the step response of the L1 adaptive controller with the amplitude equal to 1.2db, with time equal to 2 seconds, while in classical controller is same figure with nominal because it is divergent to the amplitude one and the overshoot with amplitude equal to 2.25db, with time equal 4second.



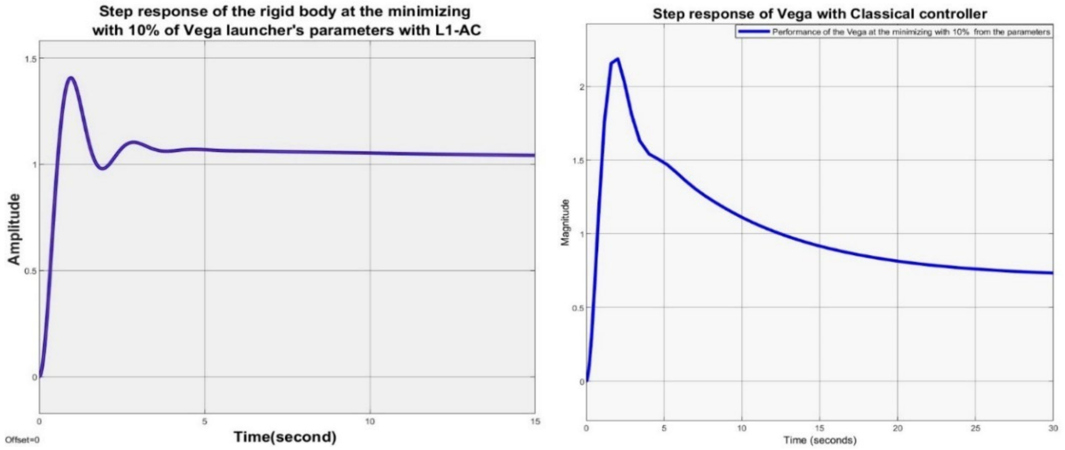
(a) Bode plot of the L1 adaptive controller (b)Bode plot of the classical controller

Fig. 8 - Bode plot of the L1 adaptive and the classical controller with Maximizing 10% of the parameters

From (Fig. 4.a) The bode plots of the L1 adaptive controller provides better margins (gain margin = 59.1.8) and better eigenvalues as compared to the classical PD controller has the same margin of the nominal (gain margin = -8.26) in (Fig. 4.b) and bad eigenvalues.

The eigenvalues for the L1 adaptive controller	the eigenvalues of the classical controller
-0.9236 + 1.5842i	-1.9219
-0.9236 - 1.5842i	1.8467
-0.1602 + 0.0000i	0.0451

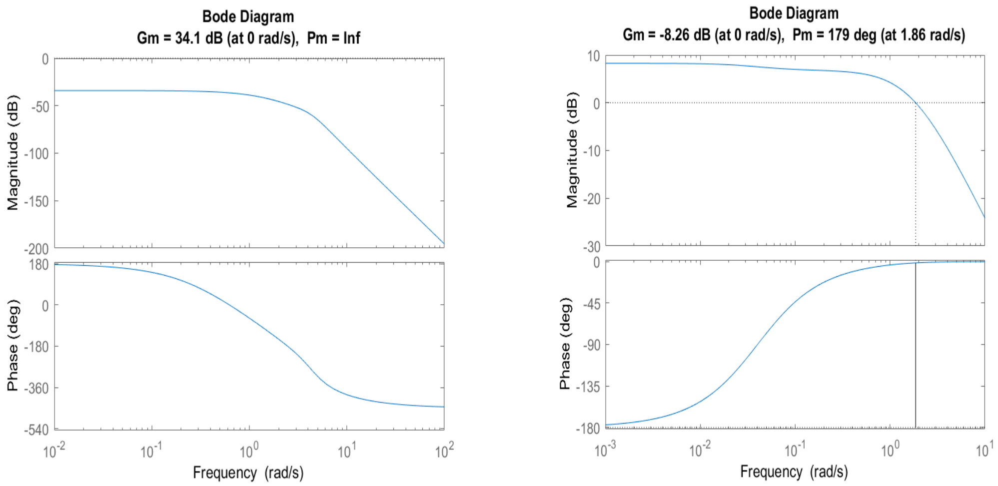
In case 3. We replacing the parameters with the minimizing with 10% in case of the classical and L1 adaptive controller such as: $a_1 = 34.083$, $a_2 = 0.024633$, $a_3 = 22.986$, $a_6 = 2.90673$ and $k_1 = 6.36642$.



(a) Step response of the L1 adaptive controller (b) Step response of the classical controller

Fig. 9 - Step responses of L1 adaptive and classical controller of rigid body with Minimizing 10% of parameters

From (Fig. 5.b) The classical controller is unable to deal with this much amount of variation and the systemic becoming critically stable however system, but with the L1 adaptive controller in (Fig 5.a) the system is stable and very close to 1, and provides a good response and the overshoot of the step response of the L1 adaptive controller with the amplitude equal to 1.4db, with time equal to 3 seconds, while in classical controller is same figure with nominal because it is divergent to the amplitude one and the overshoot with amplitude equal to 2.45db, with time equal 5second.



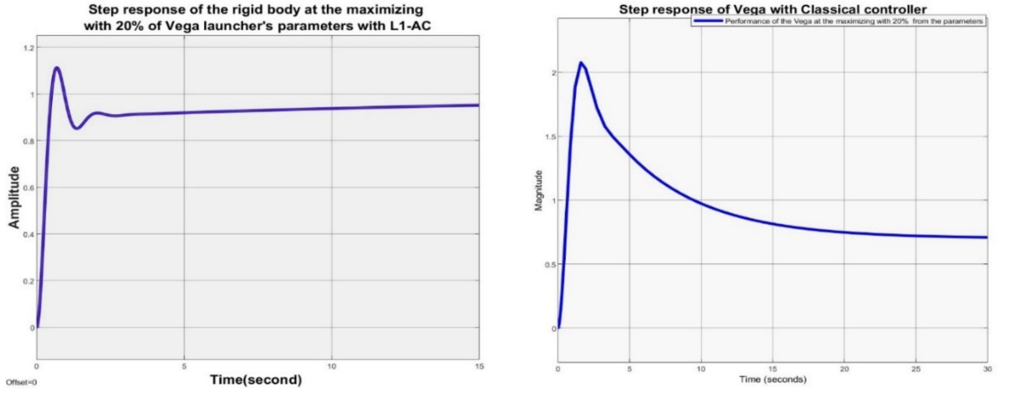
(a) Bode plot of the L1 adaptive controller (b) Bode plot of the classical controller

Fig. 10 - Bode plot of the L1 adaptive and the classical controller with Minimizing 10% of the parameters

From (Fig. 6.a) The bode plots of the L1 adaptive controller provides better margins (gain margin = 34.1) and better eigenvalues as compared to the classical PD controller has the same margin of the nominal (gain margin = -8.26) in (Fig. 6.b) and bad eigenvalues.

The eigenvalues for the L1 adaptive controller	the eigenvalues of the classical controller
-0.7564 + 1.4864i	-1.7353
-0.7564 - 1.4864i	1.6737
-0.1296 + 0.0000i	0.0369

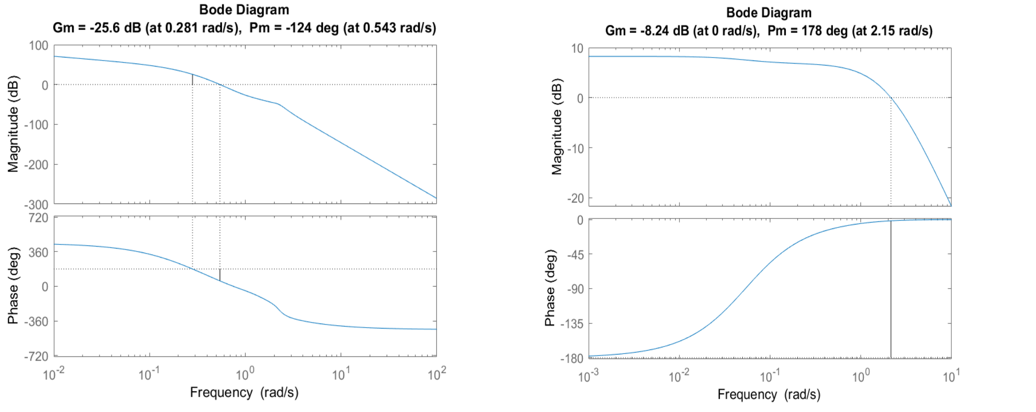
In case 4. We replacing the parameters with the maximizing with 20% in case of the classical and L1 adaptive controller such as: $a_1 = 45.4440$, $a_2 = 0.0328$, $a_3 = 30.6480$, $a_6 = 3.8756$and $k_1 = 8.4840$.



(a) Step response of the L1 adaptive controller (b) Step response of the classical controller

Fig. 11 - Step responses of L1 adaptive and classical controller of rigid body with Maximizing 20% of parameters

From (Fig. 7.b) The classical controller is unable to deal with this much amount of variation and the systemic becoming critically stable however system, but with the L1 adaptive controller in (Fig. 7.a) the system is stable and very close to 1, and provides a good response and the overshoot of the step response of the L1 adaptive controller with the amplitude equal to 1.1db, with time equal to 2 seconds, while in classical controller is same figure with nominal because it is divergent to the amplitude one and the overshoot with amplitude equal to 2.15db, with time equal 4 second.



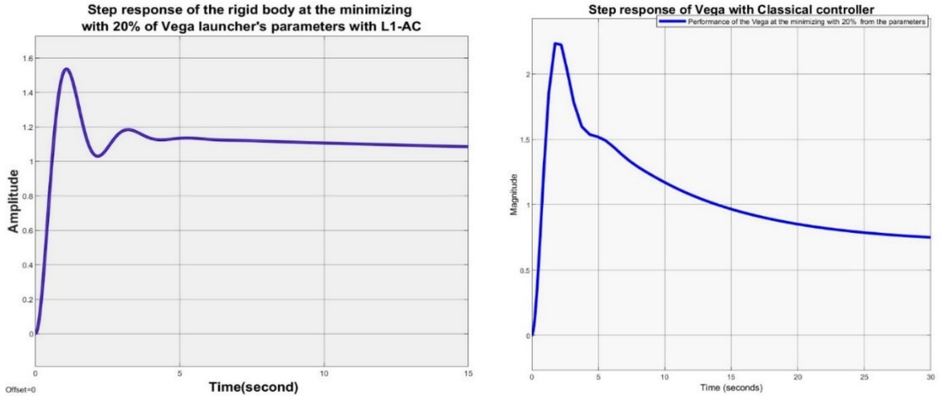
(a) Bode plot of the L1 adaptive controller (b) Bode plot of the classical controller

Fig. 12 - Bode plot of the L1 adaptive and the classical controller with Maximizing 20% of the parameters

From (Fig. 8.a) The bode plots of the L1 adaptive controller provides margins (gain margin = -25.6) and better eigenvalues as compared to the classical PD controller has the same margin of the nominal (gain margin = -8.24) in (Fig. 8.b) and bad eigenvalues.

The eigenvalues for the L1 adaptive controller	the eigenvalues of the classical controller
-1.0064 + 1.6219i	-2.0091
-1.0064 - 1.6219i	1.9270
-0.1759 + 0.0000i	0.0493

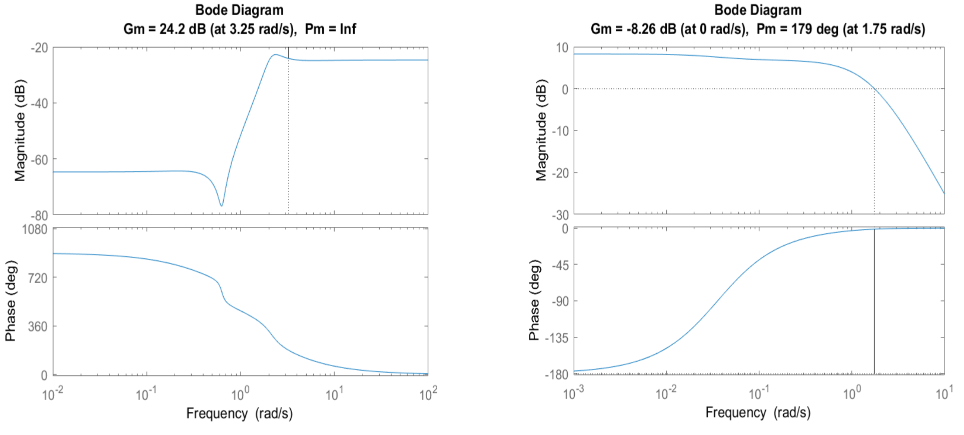
In case 5. We replacing the parameters with the minimizing with 20% in case of the classical and L1 adaptive controller such as: $a_1 = 30.2960$, $a_2 = 0.0219$, $a_3 = 20.4320$, $a_6 = 2.5838$ and $k_1 = 5.6560$.



(a) Step response of the L1 adaptive controller (b) Step response of the classical controller

Fig. 13 - Step responses of L1 adaptive and classical controller of rigid body with Minimizing 20% of parameters

From (Fig. 9.b) The classical controller is unable to deal with this much amount of variation and the systemic becoming critically stable however system, but with the L1 adaptive controller in (Fig. 9.a) the system is stable and close to 1, and provides a good response and the overshoot of the step response of the L1 adaptive controller with the amplitude equal to 1.55db, with time equal to 3 seconds, while in classical controller is same figure with nominal because it is divergent to the amplitude one and the overshoot with amplitude equal to 2.6db, with time equal 5 second.



(a) Bode plot of the L1 adaptive controller (b)Bode plot of the classical controller

Fig. 14 - Bode plot of the L1 adaptive and the classical controller with Minimizing 20% of the parameters

From (Fig. 10.a) The bode plots of the L1 adaptive controller provides better margins (gain margin = 24,2db) and better eigenvalues as compared to the classical PD controller has the same margin of the nominal (gain margin = -8.26) in (Fig. 10.b) and bad eigenvalues.

The eigenvalues for the L1 adaptive controller	the eigenvalues of the classical controller
-0.6722 + 1.4251i	- 1.6344
-0.6722 - 1.4251i	1.5797
-0.1147 + 0.0000i	0.0328

By comparing the system performance with the classical PD controller and the L1 adaptive controller it can be easily seen that the L1 adaptive controller provides better robustness along with less settling time, less overshoot, and more amount of margin. Hence it can be concluded that the L1 adaptive controller provides a better response than the classical controller.

5. CONCLUSIONS

By comparing the system performance with the classical PD controller and the L1 adaptive controller it can be easily seen that the L1 adaptive controller provides better robustness along with less settling time, less overshoot, and more amount of margin. Hence it can be concluded that the L1 adaptive controller provides a better response than the classical controller. The performance bounds can be systematically improved by increasing the adaptation rate. The adaptation bounds can be improved by increasing the rate of adaptation, while the robustness bounds can be appropriately addressed via known methods from linear systems theory. The L1 adaptive controller ensures uniformly bounded transient and steady-state tracking for both system's signals, input, and output, as compared to the same signals of a bounded reference LTI system, which assumes partial cancelation of uncertainties within the bandwidth of the control channel. It has guaranteed transient response for the system's signals, input, and output, simultaneously, in addition to stable tracking. The results of the simulations carried out showed that the adaptive amplification provided a sufficient improvement in the performance and avoided the loss of the vehicle in both nominal and extreme situations. It has been observed that the L1 adaptive control system has a better performance response compared to the control system with a classical PD controller and it can guarantee stability.

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