International Journal of Engineering

Journal Homepage: www.ije.ir

Modified L_1 Adaptive Control Design for Satellite FMC Systems with Actuators Time Delay

M. Nosratolahi*, A. Soleymani, S. H. Sadati

Department of Aerospace Engineering, Malek-Ashtar University of Technology, Tehran, Iran

PAPER INFO

Paper history:
Received 12 July 2018
Received in revised form 20 August 2018
Accepted 26 October 2018

Keywords:
Modified L_1 Adaptive Control
Time Delay
Predictive Observer
Fluidic Momentum Controller
Satellite Attitude Control System

ABSTRACT

A modified method for satellite attitude control system in presence of novel actuators is proposed in this paper. The attitude control system is composed of three fluidic momentum controller (FMC) actuators that are used to control Euler angles and their dynamics is considered in satellite attitude equations as well. L_1 adaptive control is utilized for satellite three-axial stabilization. A significant characteristic of L_1 adaptive control structure is that robustness is guaranteed in presence of fast adaptation. The main achievement of this controller is that the error norm is inversely proportional to the square root of adaptation gains. Therefore, large values of gains provides some advantages. The proposed L_1 adaptive control is designed based on simplified attitude dynamic equations without satellite coupling effects, and then it is placed on coupled nonlinear equations. Next, the impact of available delay on FMC actuators is investigated. Simulation results suggest that the system remains stable with the assumption of actuators time delay, but it experiences some oscillations in Euler angles, control inputs and angular velocities. In order to solve this problem, a modified L_1 adaptive control system including a predictive observer with high estimation speed is used. Finally, it is recognized that the available oscillations are reduced even when the actuator time delay increases and thus the control system's performance improves.

***doi**: 10.5829/ije.2018.31.11b.23*

1. INTRODUCTION

Stability and attitude control of satellites in different situations is an essential part of satellite design. Since mathematical models, which are employed for satellites control, are usually highly nonlinear and of a high degree, it is imperative to utilize a controller whose designs could be implemented based on simplified satellite models and then extended to complicated models. There are various viewpoints in designing control systems for satellites among which Model Reference Control is of notable importance. In this controller, the designer guides the system to reach a desired model or pattern after design a reference model or using available models. One of the main drawbacks of this method is that the oscillations increase as the adaptation gain rises. In other words, the adaptation gain must increase whenever the system wishes to have a desired speed in response to different inputs. Since stable methods have been used, an increase in adaptation gains may not lead to system instability but it may disturb its performance particularly through undesired oscillations. Therefore, we could assume that the main drawback of model reference method is performance disorder due to increasing the adaptation gain. It should be noted that these oscillations usually are seen in high frequencies.

In L_1 adaptive control method, applying a low-pass filter to the control inputs filters undesired oscillations, which are created because of large adaptation gain. Even though applying a low-pass filter seems to be a simple task, two problems may occur. The first one is disturbing the stable design structure of adaptive system and the second is altering its reference model pattern.

*Corresponding Author Email: *nosratolahi@mut.ac.ir* (M. Nosratolahi)

Please cite this article as: M. Nosratolahi, A. Soleymani, S. H. Sadati, Modified L_1 Adaptive Control Design for Satellite FMC Systemswith Actuators Time Delay, International Journal of Engineering (IJE), IJE TRANSACTIONS B: Applications Vol. 31, No. 11, (November 2018) 1982-1990

L_1adaptive controller transforms into a practical controller by solving these two problems.

System robustness despite fast adaptation is the main characteristic of this control method, which brings about uniform operational bounds in both transient and steady states [1]. These properties are achieved using an appropriate formulation of control target and by knowing that uncertainties in the feedback loop could not be compensated out of the control system bandwidth.

In this structure, adaptation speed is restricted only by CPUs. Because this theory guarantees remaining within the time delay margin and predicts the response of the closed loop system, Few Monte-Carlo simulations are required to investigate the system robustness. This guarantee depends on the special structure of the proposed system and the type of utilized filter as well [2]. L_1 controller structure assures that the input and output of a linear system with uncertainty, tracks the input and output of a desired linear system during transient state and asymptotic tracking is performed as well. These specifications are realized firstly by applying a model reference adaptive control, whose main difference with conventional model reference adaptive control is in the definition of error signal for adaptation rules. This new structure, which is named companion model adaptive control (CMAC), provides the possibility to apply a low-pass filter for feedback loop in order to achieve the desired transient response of the system by increasing the adaptation gain. In order to prove the asymptotic stability of the system, the L_1 gain, including filter and reference model, is required to be less than a certain coefficient [3,4]. This coefficient would be the inverse of the upper bound of the norm of unknown parameters.

Initial results of L_1 adaptive control is were pointed out by Hovakimyan and Cao [3]. In this paper, primitive theories and stability proofs are discussed. Two years later, L_1 adaptive control was implemented on a flexible launch vehicle [5]. A book [6] was authored by inventors of L_1 adaptive control method, which presents general theories and ideas with flight control applications. In addition, L_1 adaptive controller based on output feedback was developed for minimum-phase systems [7]. Also, multi criteria were presented for the design of available low-pass filter in the controller [8]. Lee and Singh [9] first extracted an analytical model of a satellite with flexible appendages, which was modeled as a Cantilever Euler-Bernoulli Beam, and then designed an L_1 adaptive controller for it after linearization in presence of parameters uncertainties and disturbances. Elahidoost et al. [10] performed a satellite orbit stabilization using L_1 adaptive control and compared their results with PD controller. Vogel et al. [11] were able to control a satellite with magnetic momentum actuators using L_1 controller. Utilization of magnetic coils as actuators imposed limitations for satellite control all of which are considered in L_1 controller design.

The literature on fluidic momentum actuators in satellite attitude control is not extensive. The earliest work on this concept was conducted by Maynard [12]. This author proposed a fluidic momentum controller to neutralize the disturbance torque exerted on spacecraft, ocean ships, and other suspended systems. Research on fluidic actuators was later extended by Lurie and Schier [13], also Iskenderian [14]. These researchers considered further details of the system, such as using pumps, hydraulic actuators and valves to control the fluid flow. Although the fluid rings may be arbitrary in shape so as to fit into the available space in a satellite and produce the maximum torque possible, the fluid should flow at the largest feasible distance around the satellite. In another study, Laughlin et al. [15] proposed a dual-function system to both measure the attitude angles of a satellite and generate a control torque. This system consists of a permanent magnet and a ring filled with a conductive fluid. The aforementioned studies, although proposing fluidic actuators, deal only with the concepts and do not involve a rigorous feasibility analysis for real applications. In this regard, Kelly et al. [16] tested the performance of a Fluidic Momentum Controller (FMC) in an experimental setup with two fluid rings whose axes of symmetry are parallel. Kumar [17] also proposed a similar fluidic actuator. This author examined the three dimensional attitude control of a satellite with fluid rings mounted on three orthogonal axes. To study the rotational motion of this satellite, a dynamical model was developed; however this model does not include all reaction moments transferred between the satellite and the fluid rings. In fact, a complete dynamical analysis of a satellite with fluid rings has not been performed yet. The failure of a fluid ring leaves it as a damper in the system, which may cause instability due to energy dissipation. Among other works, a new concept was proposed by Varatharajoo [18] which combines the attitude and thermal control systems. The main idea behind this system is based on electrically conductive fluid flows. The electric current flowing through the bypass duct exposed to thermal gradient, was produced [19]. Recently, Nobari and Misra [20, 21] improved Kumar's model [17] by developing a more complete version. They suggested a four ring fault tolerant system using a fluid flow that have been developed in a pyramidal configuration. Using sliding mode control approach, they could control the mentioned model as well [22].

However, one of the main challenges in implementing such actuators is the complex procedure of deriving a mathematical model. This causes many researchers to use a simplified model for control system design without considering uncertainty in this simplified model. Taghavi et al. [23] eliminated this problem with an adaptive sliding mode control. Their control method is not only robust with respect to uncertainties but also can estimate over their threshold without the necessity to use larger and heavier actuators to ensure satellite stability. According to the results, it is observed that the proposed control system is capable of enabling the satellite to reach the desired attitude in minimum time and without overshoot [23].

Incontinuingof development of the appropriate control solutions for FMC actuators and their evaluation of performance on satellite attitude control, in the present paper a modified L_1 adaptive control for attitude control system design is considered. The main reason for this choice is that there has been a time delay in actuators (FMCs) that had been discovered in a latest researches [24, 25].

The contributions of the present paper compared to the aforementioned research is the use of a predictive observer instead of a linear observer. This observer will observe delays which are caused in FMCs pumps that can reduce system performance. Therefore, in the next section, first, the satellite dynamic equations with FMC actuators are derived in the form of a coupled set of equations. Next, the equations of L_1 adaptive control theory are derived with predictive observer and compared to original L_1 adaptive control with linear observer. In the next stage, by creating coupling between satellite's channels and without any changes in control system parameters, it is observed that the performance of the system deviated from its desirable mode. As a result, by creating time delay on FMCs pumps and considering channel couplings, it is observed that the control system performance experiences oscillations in settling time, which can be damped and removed by the proposed L_1 adaptive controller within a short period of time. Finally, the simulation results of satellite attitude control with linear observer (original L_1 adaptive control) and the predictive one (modified L_1 adaptive control) are compared.

2. SATELLITE DYNAMIC MODEL

The body-fixed frame of reference is defined as follows: the origin is located at the mass center of the satellite. The Y_0 axis is perpendicular to the orbital plane, the Z_0 axis is directed towards the center of the earth and X_0 is determined so as to obtain a right-handed coordinate system. The orientation of the satellite at an arbitrary instant is described by roll, pitch and yaw angles about X, Y, and Z axes of the satellite body frame, respectively [21].

The motion equations of the satellite and the fluid rings may be derived as follows [21]:

$$I_s \dot{\omega} + \omega \times I_s \omega = \tau_{gg} + \sum_{i=1}^{3} R_i \tau_{ri} + \tau^c \quad i = 1,2,3 \tag{1}$$

$$\begin{aligned} & I_{fi} (R_i^T \dot{\omega} + \ddot{\beta}_i + R_i^T \omega \times \dot{\beta}_i) + R_i^T \omega \times \\ & I_{fi} (R_i^T \omega + \dot{\beta}_i) = -\tau_{ri} + R_i^T \tau_{ggfi} - \tau_i^c \end{aligned} \tag{2}$$

where, I_s , I_f are the inertial matrix of the satellite and the fluid ring, respectively. ω is the satellite angular velocity, $\dot{\beta}$ is the fluid angular velocity. τ_{gg} and τ_{ggf} are the gravity gradient torques exerted on the satellite and the fluid ring, respectively, while τ^c denotes the control torque. $\tau_r = \begin{bmatrix} \tau_{r1} & \tau_{r2} & \tau_{rf} \end{bmatrix}$ is the reaction torque, where τ_{r1} and τ_{r2} are reaction moments exerted by the fluid ring on the satellite and τ_{rf} is the fluid friction torque [21].

3. FMC DYNAMIC MODEL

The novel actuators have recently suggested that fluid motion in circular rings is used to produce angular momentum. These actuators are called Fluidic Momentum Controllers (FMCs). The FMC is because most of its mass farthest from the axis of rotation, moment of inertia of fluid rings relative to a reaction wheels with the size and weight is much higher. As a result, the torque applied ratio of their weight or volume are more suitable for using in small satellites. Also, if using of the electromagnetic or thermoelectric pumps, further had not required to electrical pumps, and in this method, the layout makes it easier for this satellite attitude control systems to another actuators. These actuators can be used as well as the failures of the control system are still capable of satellite stabilization. The FMCs is transmitted minimal vibration to the satellite structure. The circulation of the fluid inside the ring can be used as cooling. The FMC system considered consists of a satellite with fluid rings under two configuration (3-Axis and pyramidal). In the novel actuator, it is assumed that the center of mass of each of the fluid rings coincides with satellite. Separating the satellite from the fluid rings, the equations of motion can be derived for each component; that in this research, 3-Axis configuration is considered.

Fluid friction torque caused by the fluid shear stress. To find this torque, the shear stress should be integrated over the inner area of the ring that results in the fluid friction force. The control torque can then be calculated from this force. The model adopted for the shear stress is stated below[21]:

$$\tau_i = \frac{1}{8} f \rho {v_i}^2 = \frac{1}{8} f \rho r^2 {\dot{\beta}_i}^2 \tag{3}$$

where r is the ring radius, ρ is the fluid density, and f is the friction coefficient [21]. For laminar flow, the friction coefficient can be found as follows [21]:

$$f = \frac{64}{R_n} \tag{4}$$

where R_n is the Reynolds number. For the turbulent flow, the friction coefficient is given below:

$$f = \frac{0.3164}{{R_n}^{0.25}} \tag{5}$$

Multiplying the shear stress by its arm of friction (r), and then integrating this element of moment over the wetted area yields the friction torque [21]:

$$\tau_{fi} = \mathrm{sgn}(\dot{\beta}_i) 2\pi^2 \tau_i r^2 d \cong 16\pi^2 r^3 \mu \dot{\beta}_i \qquad i = 1,2,3 \tag{6}$$

where d is the diameter of the cross-sectional area of the ring. In Equation (6), it is assumed that the cross-sectional diameter of the fluid ring d is much smaller than the radius r of the ring itself($r \gg d$).

The satellite with three fluid rings is depicted in Figure 1. The part (a) is illustrated layout of FMC rings and their pumps to satellite body framebased on 3-Axis configuration. Separating the satellite from the fluid rings, the equations of motion can be derived for each component; the free body diagram of a fluid ring is illustrated in part (b).

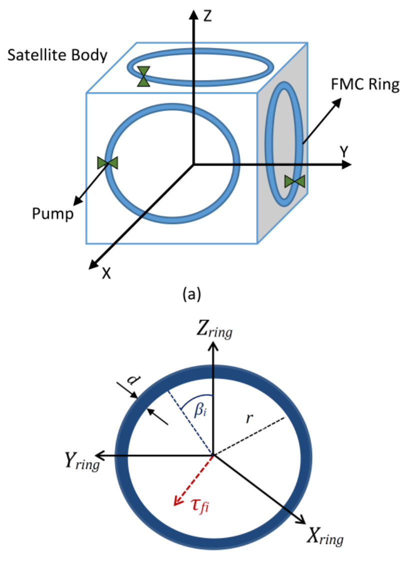

Figure 1. The satellite attitude control system with three FMCs

4. MODIFIED L_1 ADAPTIVE CONTROL

4. 1. Problem Formulation Consider the following system dynamics [6]:

$$\begin{aligned} &\dot{x}(t) = A_m x(t) + b(\phi u(t-\tau) + \theta^{\mathrm{T}}(t) x(t) + \sigma(t)) \\ &y(t) = c^{\mathrm{T}} x(t) \qquad x(0) = x_0 \end{aligned} \tag{7}$$

where $x \in R^n$ is the system state vector (measurable), $u \in R$ is the control signal, $y \in R$ is the regulated output, $b, c \in R$ are known constant vectors, A_m is a known $n \times n$ Hurwitz matrix with (A_m, b) controllable, τ is the time delay, $\phi \in R$ is a known parameter, $\theta(t) \in R^n$ is a vector of time-varying unknown parameters and $\sigma(t) \in R$ is a time-varying disturbance.

Without loss of generality, we assume that:

$$\theta(t) \in \vartheta, \quad |\sigma(t)| \le \Delta, \quad t \ge 0 \tag{8}$$

where, ϑ is a known compact set and $\Delta \in R^+$ is a known (conservative) L_∞ bound of $\sigma(t)$.

The control objective is to design a full-state feedback adaptive controller to ensure that $y(t)$ tracks a given bounded reference signal $r(t)$ both in transient and steady state, while all other error signals remain bounded.

It is assumed that $\theta(t)$ and $\sigma(t)$ are continuously differentiable and their derivatives are uniformly bounded, i.e.

$$\|\dot{\theta}(t)\|_2 \le d_\theta < \infty, \quad |\dot{\sigma}(t)| \le d_\sigma < \infty, \quad \forall t \ge 0 \tag{9}$$

where $\|\ldots\|_2$ denotes the 2-norm, while the numbers d_θ, d_σ can be arbitrarily large [26].

4. 2. State Predictor Consider the following state predictor:

$$\begin{aligned} &\dot{\hat{x}}(t) = A_m \hat{x}(t) + b(\hat{\phi} u(t-\tau) + \hat{\theta}^{\mathrm{T}}(t) x(t) + \hat{\sigma}(t)) \\ &\hat{y}(t) = c^{\mathrm{T}} \hat{x}(t) \qquad \hat{x}(0) = x_0 \end{aligned} \tag{10}$$

which has the same structure as the system in Equation (7). Consider a more general structure for the predictor as compared to Equation (7):

$$\begin{aligned} &\dot{\hat{x}}(t) = A_m \hat{x}(t) + b(\hat{\phi} u(t-\tau) + \hat{\theta}^{\mathrm{T}}(t) x(t) + \hat{\sigma}(t)) \\ &-k_{sp}(\hat{x}(t) - x(t)) \\ &\hat{y}(t) = c^{\mathrm{T}} \hat{x}(t) \quad , \quad \hat{x}(0) = x_0 \end{aligned} \tag{11}$$

where $k_{sp} \in R^{n \times n}$ can be used to assign faster poles for $(A_m - k_{sp})$. Because of having different and faster poles for the prediction error dynamics as compared to the original $(sI-A_m)^{-1}b$, prediction error dynamics will be faster. This predictive observer can be used instead of linear observers in original L_1 adaptive control for resolving the issue of actuators time delay. In other words, the modified method uses this observer instead of the original linear observer.

Parameters $\theta(t)$, $\sigma(t)$, ϕ are replaced by their adaptive estimates $\hat{\theta}(t)$, $\hat{\sigma}(t)$, $\hat{\phi}$ that are governed by the following adaptation laws[6].

4. 3. Adaptation Law Adaptive estimates are given below [6]:

$$\dot{\hat{\theta}}(t)=\Gamma_\theta \text{Proj}(\hat{\theta}(t),-x(t)\tilde{x}^{\mathrm{T}}(t)\text{Pb}),\quad \hat{\theta}(0)=\hat{\theta}_0 \tag{12}$$

$$\dot{\hat{\sigma}}(t)=\Gamma_\sigma \text{Proj}(\hat{\sigma}(t),-\tilde{x}^{\mathrm{T}}(t)\text{Pb}),\quad \hat{\sigma}(0)=\hat{\sigma}_0 \tag{13}$$

$$\dot{\hat{\phi}}(t)=\Gamma_\phi \text{Proj}(\hat{\phi}(t),-\tilde{x}^{\mathrm{T}}(t)\text{Pb}),\quad \hat{\phi}(0)=\hat{\phi}_0 \tag{14}$$

where $\tilde{x}(t) \triangleq \hat{x}(t)-x(t)$ is the error signal between the state of the system and the state predictor, $\Gamma \in R^+$ is an adaptation gain, and P is the solution of the algebraic equation $A_m^{\mathrm{T}}P+PA_m=-Q$, $Q>0$ [26].

4. 4. Control Law The control signal is generated as follows [26]:

$$u(s)e^{-\tau s}=\zeta(s)\frac{k_g r(s)-\theta^{\mathrm{T}}(s)x(s)e^{-\tau s}-\sigma(s)}{\phi} \tag{15}$$

Where:

$$k_g=-\frac{1}{c^{\mathrm{T}}A_m^{-1}b} \tag{16}$$

$$\zeta(s)=C(s)e^{-\tau s} \tag{17}$$

While $C(s)$ is any strictly proper stable transfer function with low-pass gain $C(0)=1$. One simple choice is:

$$C(s)=\frac{\omega_a}{s+\omega_a} \tag{18}$$

Furthermore, let:

$$L=\max_{\theta\in\Theta}\sum_{i=1}^{n}|\theta_i| \tag{19}$$

where θ_i is the ith element of θ and Θ is the compact set defined in Equation (8). For L_1 gain stability requirement, $C(s)$ must de designed to ensure that:

$$L\left[\|H(s)\zeta(s)\|_{L_1}+\|H(s)\|_{L_1}\right]<1 \tag{20}$$

where $H(s)=(sI-A_m)^{-1}b$.

4. 5. Proofing Let reference system of Equation (7) and (15) be defined as follows:

$$\begin{aligned}\dot{x}_{ref}(t)&=A_m x_{ref}(t)+b\left(\phi u_{ref}(t-\tau)+\right.\\&\left.\theta^{\mathrm{T}}(t)x_{ref}(t)+\sigma(t)\right)\end{aligned} \tag{21}$$

$$\begin{aligned}&u_{ref}(s)e^{-\tau s}=\\&C(s)e^{-\tau s}\frac{k_g r(s)-\theta^{\mathrm{T}}(s)x_{ref}(s)e^{-\tau s}-\sigma(s)}{\phi}\end{aligned} \tag{22}$$

Equation (21) can be rewritten as follows:

$$\begin{aligned}&x_{ref}(s)=\frac{b}{(sI-A_m)}\phi C(s)e^{-\tau s}\\&\left(\frac{k_g r(s)-\theta^{\mathrm{T}}(s)x_{ref}(s)e^{-\tau s}-\sigma(s)}{\phi}\right)+\\&\frac{b}{(sI-A_m)}\theta^{\mathrm{T}}(s)x_{ref}(s)+\frac{b}{(sI-A_m)}\sigma(s)+\\&\frac{1}{(sI-A_m)}x_{ref}(0)\end{aligned} \tag{23}$$

$$\begin{aligned}&x_{ref}(s)=H(s)\zeta(s)k_g r(s)-H(s)\zeta(s).\\&\left[\theta^{\mathrm{T}}(s)x_{ref}(s)e^{-\tau s}+\sigma(s)\right]+H(s).\\&\left[\theta^{\mathrm{T}}(s)x_{ref}(s)+\sigma s\right]+\frac{1}{(sI-A_m)}x_{ref}(0)\end{aligned} \tag{24}$$

Considering Equation (24), bound of $x_{ref}(s)$ can be extracted as follows:

$$\begin{aligned}&\|x_{ref}(s)\|_{L_\infty}\le\left\|H(s)\zeta(s)k_g\right\|_{L_1}\|r(s)\|_{L_\infty}+\\&\|H(s)\zeta(s)\|_{L_1}\left(L\left\|x_{ref}e^{-\tau s}\right\|_{L_\infty}+\|\sigma\|_{L_\infty}\right)+\|H(s)\|_{L_1}\\&\left(L\|x_{ref}\|_{L_\infty}+\|\sigma\|_{L_\infty}\right)+\left\|\frac{1}{(sI-A_m)}x_{ref}(0)\right\|_{L_\infty}\end{aligned} \tag{25}$$

Therefore:

$$\begin{aligned}&\|x_{ref}(s)\|_{L_\infty}\le\\&\frac{\left\|H(s)\zeta(s)k_g\right\|_{L_1}\|r(s)\|_{L_\infty}+\|H(s)\zeta(s)\|_{L_1}\|\sigma\|_{L_\infty}}{1-\|H(s)\zeta(s)\|_{L_1}L-\|H(s)\|_{L_1}L}+\\&\frac{\|H(s)\|_{L_1}\|\sigma\|_{L_\infty}+\left\|\frac{1}{(sI-A_m)}x_{ref}(0)\right\|_{L_\infty}}{1-\|H(s)\zeta(s)\|_{L_1}L-\|H(s)\|_{L_1}L}\end{aligned} \tag{26}$$

As a result, if $C(s)$ is designed such that Equation (20) be verified, then the closed-loop reference system in Equations (21) and (22) become stable.

The closed-loop modified L_1 adaptive control system is illustrated in Figure 2.

5. SIMULATION RESULTS

In this section, simulation results of the designed attitude control system are presented. It is assumed that the Euler angles are slightly deviated from the zero state, and the function of control system is the three-axial satellite stabilization. Orbital parameters, satellite configuration, fluidic momentum actuator parameters and controller parameters are given in Tables 1, 2, 3 and 4, respectively.

At first, it is assumed that the products of inertia are zero, and satellite channels are decoupled. A separate L_1 adaptive controller is designed for each channel. Euler angles, angular velocities, input torques of the satellite and fluid angular velocities are shown in Figures 3 to 6, respectively. The horizonal axes of Figures 3 to 26 is the orbital period which means $time/(90\times 60)$ used to indicate the number of times the satellite has completed its orbit.

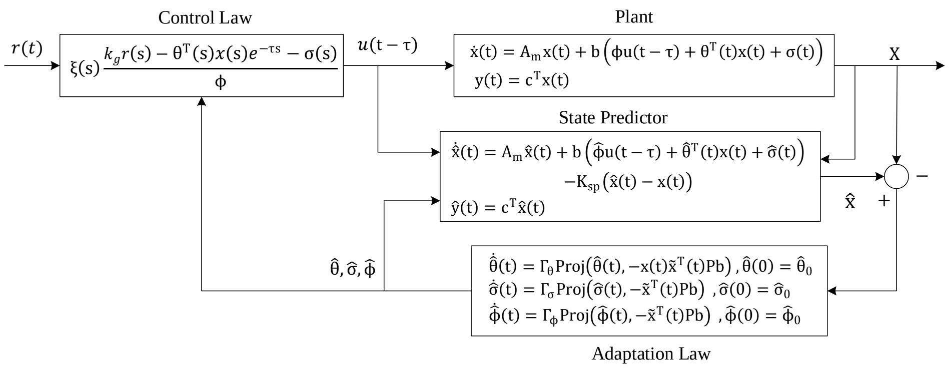

Figure 2. The modified L_1 adaptive closed-loop control system

TABLE 1. Orbital initial conditions

Orbital Elements	Value
Orbital Inclination	60 *deg*
Right Ascension of Ascending Node	120 *deg*
Argument of Periapsis	0 *deg*
Altitude Above Earth	700 *Km*
Eccentricity of Elliptical Orbit	0.0095
Orbital Period	90 *min*

TABLE 2. Initial parameters of the satellite

Parameters	Value
Initial Euler Angles	[7, 5, 11] *deg*
Moments of Inertia	[24, 28, 13] $kg.m^2$
Products of Inertia	[5, 9, 11] $kg.m^2$

TABLE 3. Initial parameters of the FMCs

Parameters	Value
Moments of Inertia	[0.048,0.048,0.048]
Fluid Density	1095 kg/m^3
Fluid Viscosity	0.06 *PA.s*
Ring Radius	0. 2 *m*
Cross Section Diameter	0.02 *m*

TABLE 4. Specification parameters of L_1Adaptive Control

Parameters	Value
A_m	[-3 -3;1 -2]
ω_a	0.001
K_{sp}	[0.35,0.32]
$\Gamma_\theta = \Gamma_\sigma = \Gamma_\phi$	10^7

As can be seen in Figures 3 to 6, satellite dynamic system is slightly slow due to small torques that are applied to the satellite by the fluidic momentum actuators.

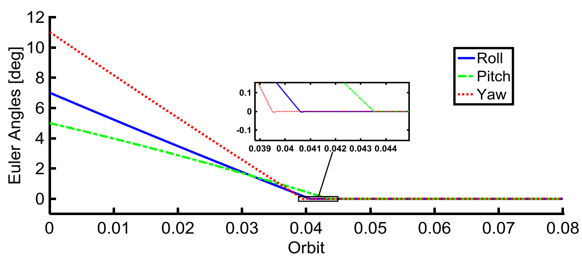

Figure 3. Satellite Euler angles for decoupled system (original L_1 adaptive control)

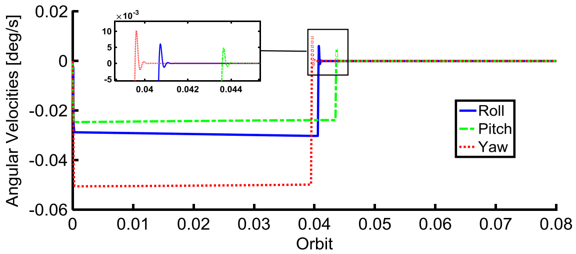

Figure 4. Satellite angular velocities for decoupled system (original L_1 adaptive control)

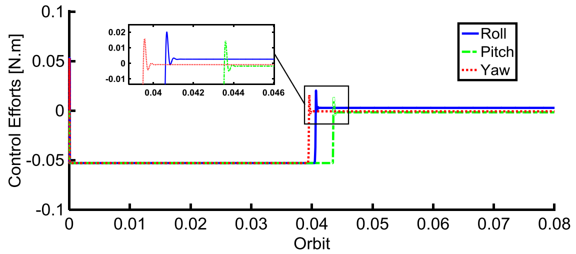

Figure 5. Control efforts for decoupled system (original L_1 adaptive control)

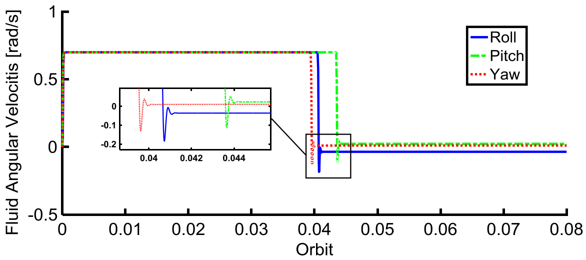

Figure 6. Fluid angular velocities for decoupled system (original L_1 adaptive control)

L_1adaptive controller has a fast response as mentioned earlier. Combining the slow and the fast dynamics of the L_1 adaptive controller has caused the responses to follow the reference input with a desired performance.

In the next stage, coupling of satellite control channels are investigated. Results show the system settling time has approximately doubled due to channels coupling, and the performance of control system is not as good as the previous case which is reasonable, because the controller is designed for the decoupled case.

In the next case, the time delay of the FMCs pumps is analyzed. Simulation is carried out with a time delay of $t = 0.05$s and channels coupling. Euler angles, angular velocities, input torques of the satellite and the fluid angular velocities for the original L_1 adaptive control and taking into account the time delay are illustrated in Figures 7 to 10, respectively.

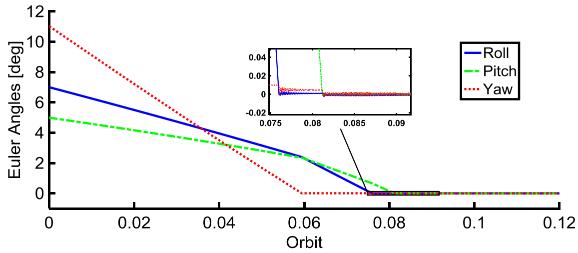

Figure 7. Satellite Euler angles for coupled system with time delay (original L_1 adaptive control)

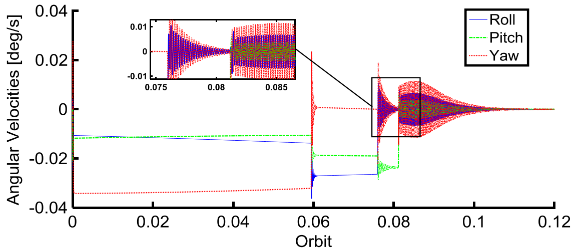

Figure 8. Satellite angular velocities for coupled system with time delay (original L_1 adaptive control)

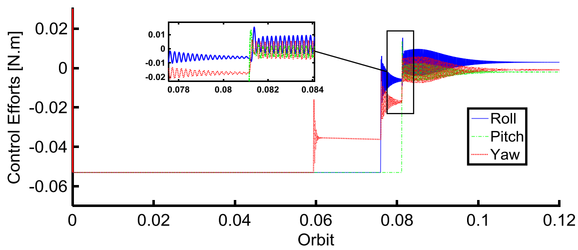

Figure 9. Control efforts for coupled system with time delay (original L_1 adaptive control)

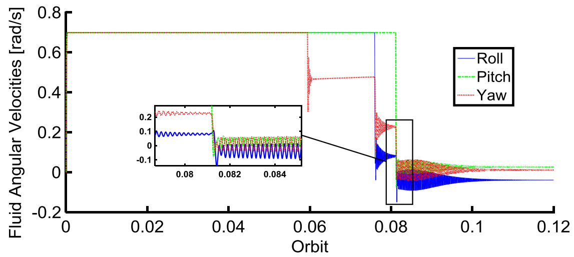

Figure 10. Fluid angular velocities for coupled system with time delay (original L_1 adaptive control)

As indicated in Figures 7 to 10, the settling time in this case has not changed compared to the previous case, but an amount of oscillations is created in the system due to time delay. Nevertheless, these oscillations are damped by the control system and eliminated within a short time. The performance of the control system with time delay and channels coupling effects on the system is acceptable in this case.

In order to resolve the aforementioned issue, a modified L_1 adaptive controller depicted in Figure 2 has investigated the results of which are displayed in Figures11 to 14. As can be observed from these Figures, the oscillations in the satellite angular velocities, fluid and control inputs have decreased considerably compared to the previous case.

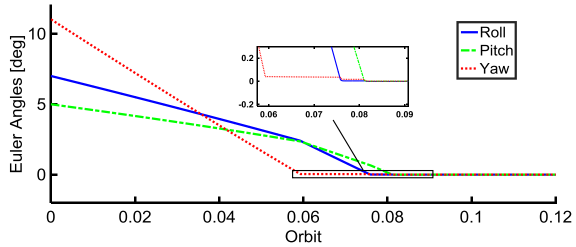

Figure 11. Satellite Euler angles for coupled system with time delay (modified L_1 adaptive control)

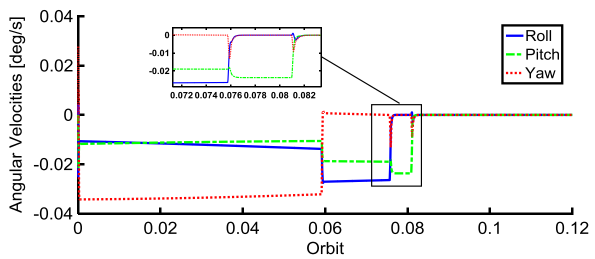

Figure 12. Satellite angular velocities for coupled system with time delay (modified L_1 adaptive control)

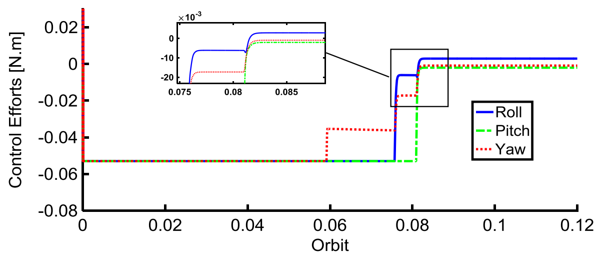

Figure 13. Control efforts for coupled system with time delay (modified L_1 adaptive control)

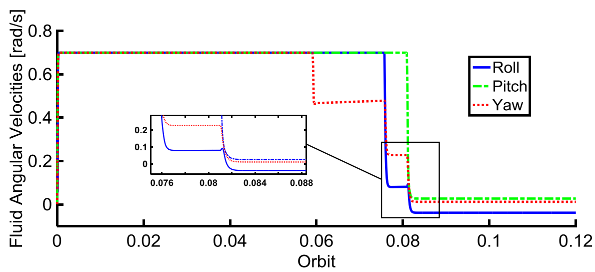

Figure 14. Fluid angular velocities for coupled system with time delay (modified L_1 adaptive control)

6. CONCLUSION

In this paper, a modified L_1 adaptive control method was employed for the attitude control of a satellite with FMC actuators. First, a dynamics model of such a system was simulated and then the proposed control method was separately designed for each control channel. Simulations indicated a slow dynamics due to the low torques produced by FMCs. Nevertheless, because of the fast adaptation characteristic of L_1 adaptive control, a highly desirable performance was obtained. In the next stage, considering channel couplings and without making any changes to the control system parameters, a performance reduction was observed in comparison with the last case. Next, it was observed that in presence of channel couplings and a time delay in FMCs pumps, the control system performance experienced oscillations during the settling time which was damped and eliminated by the L_1 adaptive controller within a short period of time. Finally, by adding a term to the observer equations, its estimation speed was enhanced, oscillations were significantly reduced and the control system performance improved considerably.

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Modified L_1 Adaptive Control Design for Satellite FMC Systems with Actuators Time Delay

M. Nosratolahi, A. Soleymani, S. H. Sadati

Department of Aerospace Engineering, Malek-Ashtar University of Technology, Tehran, Iran

P A P E R I N F O

Paper history:
Received 12 July 2018
Received in revised form 20 August 2018
Accepted 26 October 2018

Keywords:
Modified L_1 Adaptive Control
Time Delay
Predictive Observer
Fluidic Momentum Controller
Satellite Attitude Control System

چکیده

دراین مقاله یک روش اصلاحی افته برای سیستم کنترل وضعیت ماهواره درحضورعملگرهای جدید ارائه شده است. در این سیستم کنترل وضعیت ازسه عملگرد مومنتوم سیالی جهت کنترل زوایای اویلر استفاده شده ودینامیک آن ها نیز در معادلات وضعیت ماهواره لحاظ شده است. در همین راستا برای پایدار سازی سه محوره ماهواره مورد نظراز یک روش کنترل تطبیقی L_1 استفاده شده است. خصوصیت شاخص ساختار کنترل تطبیقی L_1، تضمین مقاوم بودن درحضور تطبیق سریع است. دستاورداصلی این کنترل‌کنندهها است که نرم خطاء به طور یکنواخت با معکوس ریشه مربع بهره‌های تطبیق متناسب دارد. بنابراین مقادیر زیادبهره‌های تطبیق دارای مزیت خواهند بود. کنترل تطبیقی L_1 ارائه شده براساس معادلات دینامیک وضعیت ساده شده طراحی و بدون کوپل ماهواره انجام گرفته وسپس بر روی معادلات غیرخطی و کوپل شده نیز قرار داد شده است. در مرحله بعد تاثیر تاخیر موجود درعملگرهای مومنتوم سیالی بر روی سیستم کنترلی بررسی شده است. نتایج شبیه‌سازی‌ها نشان می‌دهند که سیستم با فرض وجود تاخیر، پایدار باقی مانده ولی دچار نوساناتی در ورودی‌های کنترلی و سرعت‌های زاویه می‌شود. به منظور رفع این مشکل، از یک مشاهده‌گر پیش بین با سرعت تخمین بالاتر استفاده شد. در نهایت مشاهده شد که حتی باافزایش میزان تاخیر،نوسانات موجود کاهش یافته و عملکرد سیستم کنترلی بسیار مطلوب گشت.

***doi**: 10.5829/ije.2018.31.11b.23*