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Disturbance observer based anti-disturbance fault tolerant control for flexible satellites

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Abstract. In the field of aerospace engineering, accurate control of a spacecraft's orientation is often very important to mission success. Therefore, attitude control is a technically plentiful and extensively studied subject in controls literature during recent decades. This investigation of spacecraft attitude control is assumed to address two important aspects of the problem solutions. One sliding mode anti-disturbance control for utilization of faulty actuator components and another one disturbance observer based control to improve the pointing accuracy in the absence of anti-vibration equipment for the elastic appendages like a solar panel. Simultaneous occurrence of vibration due to flexible appendages and reaction degradation due to failure in attitude actuators complicates this case. The advantage of this method is acquisition proper control by the combination of disturbance observer and sliding mode compensation that form a fault tolerant control for the concerned satellite attitude control system. Furthermore, the proposed composite method indicates that occurrence the failure in actuators and even elastic solar panel vibration effect may be handled directly without reconfiguring the control components or providing piezoelectric devices. It's noteworthy, attitude quaternion and angular velocity commands are robustly tracked via controllers to become inclined to zero.

Keywords: attitude control; actuator failure; disturbance observer based control; sliding mode

1. Introduction

Recent decades there has been wide attention in the application of robust control in the design of attitude control laws for satellite stabilization and several control methods have been profited by spacecraft (Cao and Guo 2012, Chen *et al*. 2016, Yang 2014). Among them, the field of robust control method employing disturbance observers (DO) is one that has recently attracted a lot of attention in the spacecraft attitude control research literature (Cao, Zhao and Qiao 2016, Chi *et al*. 2015, Chu and Cui 2016, Liu, Guo and Zhang 2012a). Therefore, for the sake of attitude robustness improvement, the controller could compensate the influence of internal uncertainties

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and external disturbances concurrently Liu, Guo and Zhang (2012b).

Environmental disturbances and also uncertainties widely exist in aerospace systems and bring unfavorable effects on performance and even stability of satellite attitude. In a common case, platform vibration as a type of internal perturbation, is a source of performance degradation in high resolution remote sensing payloads Haghshenas (2017). Also, occurrence of such type of fault in attitude actuators that are uncertain for the control system is another casualty that can trouble the operation.

Owing to the fact that most of these perturbations and uncertainties are not measurable or is too costly to measure, it is offered that a feedforward strategy could eliminate or at least attenuate influence of some of them. For this, one intuitive method to cope with this obstacle is to approximate the influence of the disturbance from measurable system output and variables in the first stage and then based on the estimation, a supplementary control torque can be taken, to suppress that. Thereinafter this efficient idea expanded to deal with influence of internal (parametric and unmodeled dynamics) uncertainties where it also could be taken into account as a part of the combined disturbances. Although these algorithms known by various titles, since an observer estimates disturbances as the base of corresponding controller design, these types of control methods are mostly called disturbance observer based control (DOBC). Use of observer to estimate disturbances consisting of both unknown uncertainties and external disturbances or some of them, offers an improved system robustness; incidentally, some other engineering practices like good transient response exhibition, easy implementation and saving in control output make it more valuable (Chen *et al*. 2016, Huang and Xue 2014, Huang *et al*. 2014).

As sliding mode control is an efficient method for systems constrained by stochastic perturbation, exogenous disturbance, unknown load conditions and control input constraints, it applied in many types of difficult technical fields. The reference (Liu, Yin *et al*. 2017) introduced an extended state observer based second order sliding mode that provides a complete robustness against resistance load variation in an AC/DC Voltage Source Converter. Also a novel sliding mode control (SMC) law is presented by (Wu, Gao *et al*. 2017) applied to multi-loop control case considering types of limitation and perturbation. By (Wan, Naidu *et al*. 2017), an adaptive sliding mode control scheme is proposed for spacecraft rendezvous suffering from the external perturbations and the time-varying saturation, which can be induced by the temporal characteristics and the accidental faults of actuators. They show that this control scheme can achieve asymptotic stability without using the effectiveness information of actuators.

Employing anti-disturbance control laws accompanied by DOBC can compensate norm bounded disturbances and failures effects, forcefully. There has been wide interest in the study and application of SMC in satellite attitude control to responsible for dealing with mentioned perturbations (Hu *et al*. 2013, Hu, Li and Qi 2014, Hu and Xiao 2013, Huo, Hu and Xiao 2014, Jin and Sun 2008, Li, Wang and Fei 2011, Pukdeboon and Siricharuanun 2014, Wu *et al*. 2011, Yadegari, Chao and Yukai 2016). Due to anti-disturbance properties of this controller, in present article this robust feedback scheme; which has been receiving considerable attention for its simple implementation, relatively lower volume of calculations and insensitivity to parametric uncertainties and disturbances; is designated to execute as another part of controller. So, the combination of disturbance observer and sliding mode compensation, form an anti-disturbance fault tolerant control scheme for the concerned satellite attitude control system (ACS).

One of the earliest studies into fault tolerant control (FTC) strategy, containing a composite DOBC, for the spacecraft attitude control problem is presented in Cao, Zhao and Qiao (2016). The controller is also consisting of an adaptive compensation term to regain concerned systems composure for maintenance of system equilibrium. Zhao and Cao (2015) presented an adaptive fault tolerant method for micro-satellite attitude control with actuator faults in presence of multiple disturbances. They designed both disturbance observer and fault diagnosis observer to estimate their effects.

Some surveys can be seen concerning presentation of composite controllers, with combination of DOBC. In Chi *et al*. (2015), a kind of disturbance estimation and compensation method is proposed. Their method is based on the frequency domain disturbance observer combining with PID controller for a drag-free satellite. In Liu, Vazquez *et al*. (2017), an extended state observer is used to asymptotically reject external disturbances based on a second order sliding mode control to achieve a high performance. Another investigation by Chu and Cui (2016) proposed a fuzzy adaptive disturbance observer to approximate and then compensate effects of equivalent disturbances for a small satellite. But it focused on integrated power and attitude control and also sensor/actuator specifications. The valuable article studied by Hu, Li and Qi (2014) provided a time-varying SMC scheme with finite time convergence of both attitude and velocity with simple design procedures, in presence of above-mentioned disturbances and even actuator input saturation and misalignments based on a second-order observer to estimate the sliding surface and the differentiable disturbances for satellite ACS.

In the field of flexible satellites, Gennaro in Di Gennaro 2002, 2003, Di Gennaro 1996, by using piezoelectric actuators developed dynamic compensator to actively damp the solar array vibrations. By combining DOBC and PD control, Liu, Guo and Zhang (2011) designed a composite controller. The observer is formulated for feedforward compensation of the elastic vibration induced by these flexible elements of the satellite appendages. In another research, the same authors applied a H-infinity state-feedback control instead of PD to reject the effect of vibrations from flexible accessories Liu, Guo and Zhang (2012a).

The work in this paper attempts to introduce a DOBC approach combined with a nonlinear SMC scheme to control the attitude of a flexible satellite in presence of perturbations. Since both of these schemes are used to enhance the anti-disturbance performance, this composite method is powerful from this perspective. Which make this article interesting besides the existing works, are in three respects. First, using two robust methods to establish a composite control algorithm can present an efficient scheme. Further, such work with increased uncertainties due to flexible appendages and failure in attitude actuators simultaneously is much more challenging. In addition to a rigid main body, the flexible satellite includes some elastic appendages like solar panel or antenna. And the last, in many fields of the space industry, the simplicity of the controller design procedure is necessary for real-time implementation; so much the better, this method has this state of being special. And also for investigation of stability property of the closed-loop system a Lyapunov function is introduced too.

This article is organized as follows. This section included preliminaries and literature of study. Section 2 is mentioned some required definitions, recalling the mathematical model of a flexible spacecraft and explanation of the control problem. In section 3, the DOBC and SMC methods are developed. In a subsequent section, numerical simulations of ACS of satellite are performed to verify the performance of composite controller and also each scheme effects separately. Final section belongs to the concluding remarks and discussions.

2. Preliminaries

2.1 Definitions

In this paper; I is the identity matrix, then the norm of vector $V=\begin{bmatrix}V_1 & V_2 & V_3\end{bmatrix}^T$ denotes as $\|V\|$ and the antisymmetric tensor of it marking and forming as $V^{\times}$.

$$V^{\times}=\begin{bmatrix}0 & -V_3 & V_2\\ V_3 & 0 & -V_1\\ -V_2 & V_1 & 0\end{bmatrix} \tag{1}$$

The kinematics of motion assign the attitude of satellite body and one of the few ways to express it, are unitary quaternions $\begin{bmatrix}q_0 & q\end{bmatrix}$ with 3-dimensional vector q under the restriction of $q_0^2+q^Tq=1$ that used in this article (Hughes 2012, Sidi 1997, Wertz 2012).

2.2 Attitude dynamics and kinematics of a flexible satellite

The kinematic equations of motion take the form

$$\begin{bmatrix}\dot{q}_0 & \dot{q}\end{bmatrix}=0.5\begin{bmatrix}-q^T & q^{\times}+q_0I\end{bmatrix}\omega \tag{2}$$

As well the dynamic equation of a flexible satellite described in the body-fixed frame according to Sidi (1997), is given by Euler theorem as

$$J_t\dot{\omega}+\delta^T\ddot{\eta}=-\omega^{\times}\left(J_t\omega+\delta^T\dot{\eta}\right)+D+u \tag{3}$$

Where J_t is symmetric inertia matrix of the structure totally, including the main body as matrix J and inertia matrix due to the flexible parts. As well, δ is the coupling matrix between the elastic parts and rigid main body and η is the modal coordinate vector. The control torque u is generated by actuators and disturbance torque D by satellite surrounding environment. The flexible dynamics describes with following equation under the assumption of small elastic deformations

$$\ddot{\eta}+C\dot{\eta}+K\eta=-\delta\dot{\omega} \tag{4}$$

Moreover, C and K are the damping and stiffness matrices respectively and can be describe as $C=diag\left\{2\xi_i\omega_{ni}\right\}$ and $K=diag\left\{\omega_{ni}^2\right\}$ that $i=\left\{1,2,...,N\right\}$. Here, the number of elastic modes considered as N, the natural frequencies as ω_{ni} and the corresponding damping as ξ_i.

Substituting the second derivative of modal coordinate vector (4) into the dynamic Eq. (3), eventuates

$$J_t\dot{\omega}+\delta^T\left(-C\dot{\eta}-K\eta-\delta\dot{\omega}\right)=-\omega^{\times}\left(J_t\omega+\delta^T\dot{\eta}\right)+D+u \tag{5}$$

forasmuch as J_t including J and $\delta^t\delta$ which is the contribution of the flexible parts from the total inertia matrix, inertia matrix of the main body can describe as

$$J=J_t-\delta^T\delta \tag{6}$$

The term $\delta^T\left(C\dot{\eta}+K\eta\right)$ is motivated by flexible parts and can be supposed as a part of disturbances. Therefore, $d=\delta^T\left(C\dot{\eta}+K\eta\right)+D$ can be considered as lumped disturbances. Then

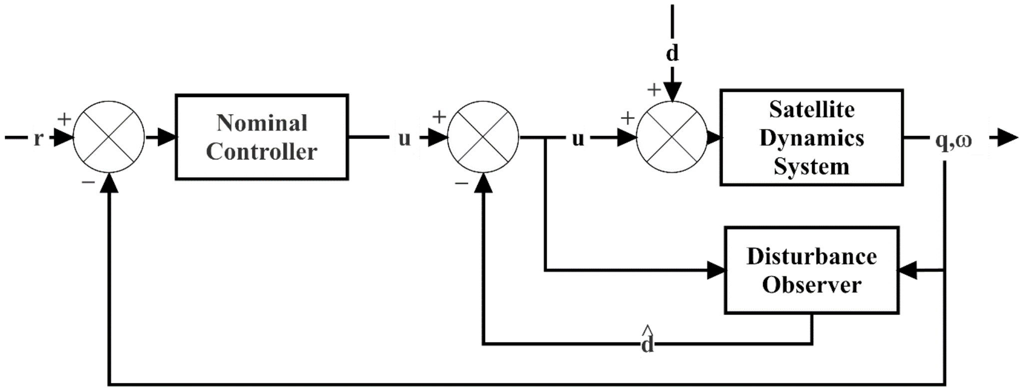

Fig. 1 Structure of proposed ACS

by substituting J and d, Eq. (5) can be found in foreshortened form of

$$J\dot{\omega}=-\omega^{\times}\left(J\omega+\delta^{T}\dot{\eta}\right)+d+u \tag{7}$$

2.3 Problem statement

In this work, the aim of ACS is to realize desired direction and to rest of the body from vibrations and other noises, at the same time. The measured variables are the attitude variables $[q_0 \quad q_v]$ and angular velocity ω. In the following a summary of this problem is made. Acquire a controller such that, achieve to $\lim_{t\to\infty} q_v = 0$ and $\lim_{t\to\infty} \omega = 0$ using mentioned measurements. It is worth noting that according to pre mentioned constraint relation, when quaternion vector elements towards zero, then $q_0 \xrightarrow{yields} 1$. Realizing desired attitude direction, can be commanded by the reaction wheels or gas jets and sometimes both of them together. But for the sake of simplicity, structure and mathematics model of these actuators is not referred to and merely attention is restricted to the required torque.

Since the aim is to design a controller without measured amount of perturbations, an estimation of them is necessary. Obtaining this information is possible by designing a disturbance observer dynamic system whose outputs are the approximations of d, while the inputs are ω and q, in the observer. The command torque u such may achieve desired attitude in the DOBC approach is proposed in the following form

$$u=\bar{u}-\hat{d} \tag{8}$$

where $\bar{u}$ is designed by SMC scheme to achieve stability; but it can be replaced with any other control method according to the nominal plant, in variant of investigations. In this relation, $\hat{d}$ is the estimation of lumped perturbations d and is responsible for compensation of their influence. The structure of the ACS is depicted in Fig. 1.

2.4 Nominal PD controller

For the sake of comparison between control schemes and also using a nominal controller for composite schemes, a simple saturated PD controller is introduced. (Shen *et al*. 2015) has asserted that in a zero-disturbance normal attitude dynamic system without any fault in attitude actuators, the controller (9) is able to stabilize satellite ACS.

$$u_{PD} = -k_p \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} - k_d \begin{bmatrix} \tanh(\omega_1/p_d) \\ \tanh(\omega_2/p_d) \\ \tanh(\omega_3/p_d) \end{bmatrix} \tag{9}$$

where k_p and k_d are positive constants, as well as sharpness function p_d is a nonzero positive scalar sharpness function. Adjustment of p_d can modify the rate of change of nominal control torque to improve dynamic performance. And also its value determines how strongly the control varies with the signal ω.

2.5 Nominal $\boldsymbol{H}_\infty$ controller

The valuable paper (Show *et al*. 2003) presents a quaternion nonlinear feedback controller law for spacecraft attitude stabilization and maneuver. In the paper, the solution is conjectured and shown to satisfy the H-infinity criterion for the satellite ROCSAT-3 orbit raising control problem. Current study tried to take advantage of H-infinity control method that presented in this article for the sake of two determinant issues. The first, most of the articles work in the field of robustness using the H_∞ method, only considered the stability of two axes, but not all tree axes like this investigation. Another intended issue is using the quaternion and angular velocity as system states that is desired same to work on current study. So, this controller application has been beneficial to this research. According to this article, the H-infinity controller is obtained as

$$u_{H_\infty} = -\frac{2}{\rho^2}\left(k_\omega \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} + k_v \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} + k_0 q_0 \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \right) \tag{10}$$

In this research, the H_∞ controller is used for comparison and evaluation of SMC performance.

2.6 Assumptions and lemma

Before expression of observer and controller, required assumptions and lemma are given.

Assumption 1. In accordance with the practical situations, the matched disturbances can be assumed to be bounded by $\|d\| \le d_{max}$, where d_{max} is a positive number.

Assumption 2. In case of appendages vibration, it is assumed that elastic deformations are small, but not to be considered as a rigid body.

Lemma. Suppose continuous positive definite function V (on $\Re^n$) such that (11) for $\alpha \in (0.1)$ and $c \in \Re^+$. Then there exist an open neighbourhood region such that any $V(x)$ which start from this region, $V(x) \equiv 0$ can be reached in finite time.

$$\dot{V}(x) + cV^\alpha(x) \le 0 \tag{11}$$

3. Composite controller design

Generally, there are three stages for design of a robust DOBC for system. First stage is designing an observer in order to estimate the disturbances. Simultaneously the observer gains should evaluate such that the accuracy of estimation meets expectations and the observer error dynamics remains stable. Second stage consists of designing a controller for the nominal system to achieve satisfactory stability, while hereon disturbances are not considered. The last stage is integrating disturbance compensation part that means the observer and nonlinear control part.

3.1 Disturbance observer design

This subsection introduces the disturbance observer. Wen-Hua Chen recommended a disturbance observer in his articles (Chen 2004, Chen *et al*. 2000, Chen *et al*. 2016). Following, his approach will be adopted to the considered ACS problem. An initial disturbance observer can be proposing as

$$\dot{\hat{d}} = L\left(J\dot{\omega} + \omega^{\times} J\omega - u\right) - L\hat{d} \tag{12}$$

Here L is the gain of observer with the form of $L = \alpha.I_{3\times 3}$ where α is a real positive number. Then substituting d obtains

$$\dot{\hat{d}} = L\left(d - \hat{d}\right) \tag{13}$$

Whereas $\dot{\omega}$ is not available, the disturbance observer (12) cannot be realized. This problem is surmounted by defining an auxiliary variable.

$$v = \hat{d} - LJ\omega \tag{14}$$

Differentiating this equation and substituting $LJ\dot{\omega}$ from (12) yields

$$\dot{v} = -L\hat{d} + L\left(\omega^{\times} J\omega - u\right) \tag{15}$$

Following (14), the approximation $\hat{d}$ of disturbance d is given by

$$\hat{d} = v + LJ\omega \tag{16}$$

Here, according to recent Eqs. (15) and (16), the disturbance observer defines as following to approximate term d. Finally, following equation, defines estimate of observer error as e.

$$e = d - \hat{d} \tag{17}$$

Theorem 1. Consider the ACS model introduced by (7), lumped disturbances can be estimated by the following disturbance observer so that estimated disturbances $\hat{d}$ converge to d.

$$\begin{cases} \dot{v} = -L\hat{d} + L\left(\omega^{\times} J\omega - u\right) \\ \hat{d} = v + LJ\omega \end{cases} \tag{18}$$

Proof: For this disturbance observer, the error dynamics can be described by

$$\dot{e} = \dot{d} - \dot{\hat{d}} \tag{19}$$

where e is estimate error of disturbance observer. Derivative of (16) gives

$$\dot{e} = \dot{d} - \dot{v} - LJ\dot{\omega} \tag{20}$$

Substituting Eqs. (7) and (15) into (20) demonstrates

$$\dot{e} = \dot{d} + L\hat{d} - L\omega^{\times}J\dot{\omega} + Lu - L\left(-\omega^{\times}J\dot{\omega} + d + u\right) \tag{21}$$

and then

$$\dot{e} = \dot{d} - L\left(d - \hat{d}\right) \tag{22}$$

According to these calculations, it can be perceived that e is governed by

$$\dot{e} = \dot{d} - Le \tag{23}$$

Therefore, assuming the disturbances are slowly time varying, derivative of their values can be supposed to be zero. So Eq. (23) can be write as

$$\dot{e} + Le = 0 \tag{24}$$

According to explained lemma, observer gain L can be design such that the observer error e is derived to zero exponentially. Hence, disturbance estimate $\hat{d}$ can approach d exponentially as $t \to \infty$. Eventually the system is exponentially stable for all ω with designed controller.

3.2 Sliding mode controller design

Fundamentally, SMC law is so that switches consecutively between two values to slide the system's state-space trajectory on desired surface. Observing conciseness, readers are referred to (Perruquetti and Barbot 2002, Slotine and Li 1991) for more articles on the topic of SMC. After proposing the DO by Eqs. (18), achieving the design target, a novel SMC scheme is investigated in this subsection.

Theorem 2. Consider the ACS model introduced by (7) with the NDO defined by (18), under the $\bar{u}$ term of control law suggested in Eq. (25).

$$\bar{u} = \omega^{\times}J\omega - \tfrac{1}{2}kS^{T}J\left(q^{\times} + q_0 I\right)\omega - k_1 S - k_2 \frac{S}{\left|S + \pi\right|} \tag{25}$$

Where k, k_1, k_2 and π are respectively control gains and a positive bounded scalar sharpness number, as well as S is sliding surface define by

$$S = \omega + kq \tag{26}$$

Then, the following goals can be achieved:

- Approaching the sliding surface to zero;
- Deriving the states q and ω to zero, in the closed-loop system.

Proof. Lyapunov candidate function can be found in the form of

$$V = \tfrac{1}{2}S^{T}J_t S \tag{27}$$

Differentiating (27), then substituting $\dot{S}$ and then $\dot{q}$ and $J\dot{\omega}$ from (2) and (7) yields to

$$\begin{aligned}\dot{V} &= S^T J \dot{S} = S^T J \left(\dot{\omega} + k\dot{q}\right) \\ &= S^T \left(-\omega^{\times}\chi + d + u\right) + \tfrac{1}{2} k S^T J \left(q^{\times} + q_0 I\right)\omega\end{aligned} \tag{28}$$

Again, substituting u from Eqs. (8) and (25) gives following Inequality.

$$\begin{aligned}\dot{V} &= S^T \left(-k_1 S - k_2 \frac{S}{|S+\pi|}\right)\omega \\ &= S^T S\left(-k_1 - k_2/|S+\pi|\right)\omega \\ &\le -\|S\|^2 \left(k_1 + k_2/|S+\pi|\right)\|\omega\|\end{aligned} \tag{29}$$

Then, by choosing positive control gains k_1 and k_2, inequality $\dot{V} \le 0$ is obtained that is prerequisite to have bounded sliding mode state S for all conditions under the law equation of control (8).

4. Numerical simulation

In this section, validity and effectiveness of proposed composite control method for ACS of a flexible satellite is considered. To achieve this purpose through numerical simulations, two techniques are advantageous; one studying the absence of DOBC part effects and the other comparing the whole control scheme with other results that published in related studies. At first, necessary values for numerical simulation are defined.

4.1 Value definition

In the procedure of simulation, the initial conditions are selected as

$$q = \begin{bmatrix} 0.62 & 0.35 & 0.25 & -0.12 \end{bmatrix} \tag{30}$$

$$\omega = \begin{bmatrix} 0.01 & 0.03 & 0.02 \end{bmatrix} red/\text{sec} \tag{31}$$

respectively for quaternion and angular velocity. According to the article Di Gennaro (2003), the matrixes of satellite momentum inertia and coupling matrices respectively

$$J = \begin{bmatrix} 350 & 3 & 4 \\ 3 & 270 & 10 \\ 4 & 10 & 190 \end{bmatrix} kg.m^2 \tag{32}$$

And

$$\delta = \begin{bmatrix} 6.45637 & 1.27814 & 2.15629 \\ -1.25619 & 0.91756 & -1.67264 \\ 1.11687 & 2.48901 & -0.83674 \end{bmatrix} \sqrt{kg}.m/s^2 \tag{33}$$

are considered. And also parameters of flexible dynamics that have been taken into account, including first three natural frequencies and damping modes used for simulating the spacecraft, respectively are chosen as

$$\omega_n = \{0.7681 \quad 1.1038 \quad 1.8733\} \tag{34}$$

And

$$\zeta = \{0.0056 \quad 0.0086 \quad 0.0130\} \tag{35}$$

The resultant of external disturbances all together are considered same as article Hu, Li and Qi (2014), given by

$$D = 2\times10^{-4} \times \begin{bmatrix} 3\cos(10\omega_d t) + 4\sin(3\omega_d t) - 10 \\ -1.5\sin(2\omega_d t) + 3\cos(5\omega_d t) + 15 \\ 3\sin(10\omega_d t) - 8\sin(4\omega_d t) + 10 \end{bmatrix} N.m \tag{36}$$

that $\omega_d = 0.1\, Rad/\sec$.

There are no exceptions; any kind of ACS actuators have a saturation limit. Here, the maximum control torque capacity of actuator is considered as a small value 1 N.m in each satellite main axis. The design parameters of the proposed control law (25) are set as Table 1.

Simulations of the model implemented in MATLAB/Simulink environment. The solver ode45 with Variable-step with maximum step size of 0.01 for integration time-step has been used in continuous system simulation.

4.2 Attitude stabilization by composite DOBC-SMC scheme

In this subsection, overall behavior of ACS governed by proposed composite controller will be illustrated. The most important factors that must be investigated are tending signals q and ω to zero. Fig. 2 shows the simulation plots for this case of initial condition by values of Table 1 controller parameters. As it seen, ACS reach this desired attitude in about 60 seconds.

Table 1 ACS parameters for simulation

Controller part	Control gain	Value
SMC	k	0.2
	k_1	1
	k_2	2
	π	0.01
H_∞	k_0	6
	k_v	6
	k_ω	65
PD	k_p	120
	k_d	100
	p_d	0.2
DOBC	α	1.7

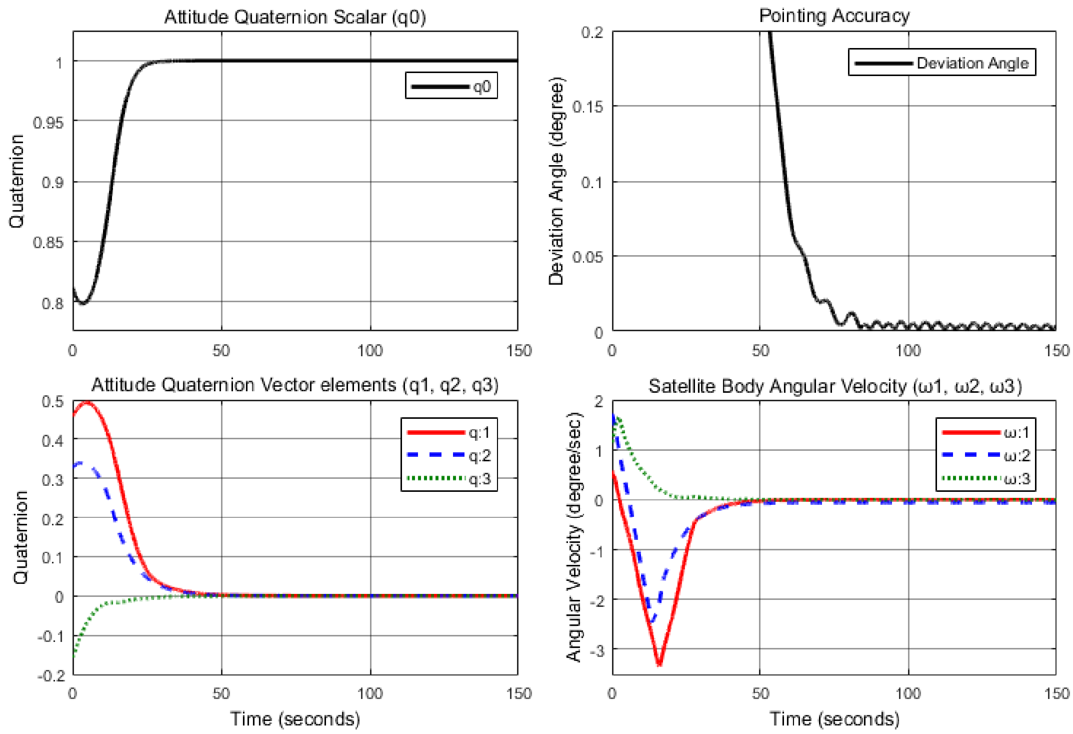

Fig. 2 Time responses of the spacecraft attitude condition using DOBC-SMC scheme

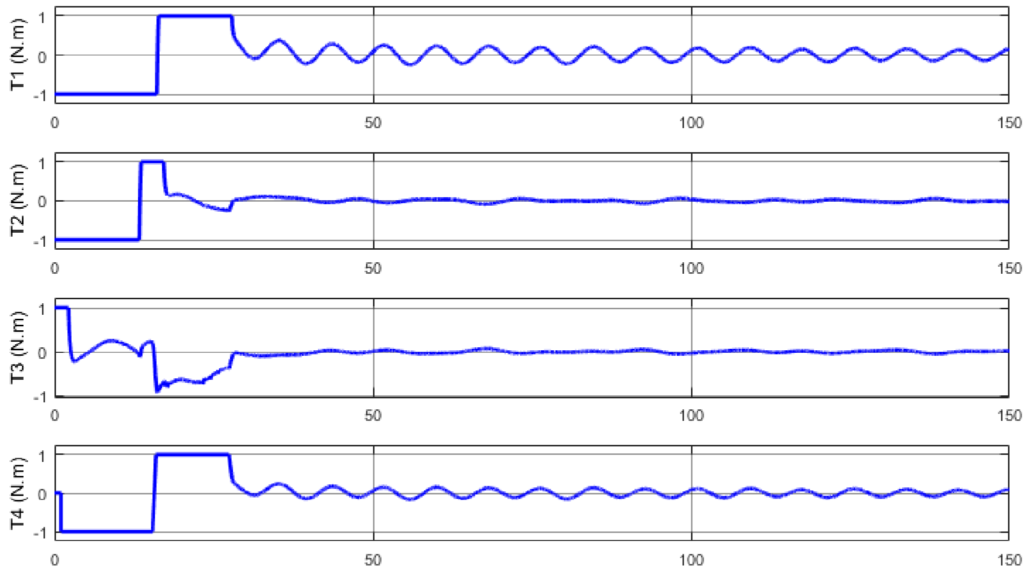

Fig. 3 Time responses of the ACS reaction wheels output

Observer gain should be designated according to the principle of tradeoff. Hence, expressing the findings from simulation is beneficial. Based on simulation, the larger observer gain L, the slower convergence and lower accuracy of quaternion system states. Also, a large L, perhaps bring the attitude system a little unstable. Anyway over a large range of observer gain, ACS has a perfect performance and also steady state error of angular velocity and quaternion are negligible, likewise control input remain at a low level. Time response of the control output is shown in Fig. 3, that the restriction of 1 N.m for control torque magnitude is apparent.

Another criterion in setting of this gain is the ability of observer to estimate disturbances and bringing the observer error to minimum value. Fig. 4 illustrating lumped disturbances drawn with dashed line chase by the observer drawn with continuous line in each axis. This chasing can be seen in steady state condition, clearly. It should be noted, since $L = \alpha . I_{3\times 3}$, during the examination just α set.

In case of SMC performance, Fig. 5 indicates driving the sliding surface of the designed sliding mode controller to zero.

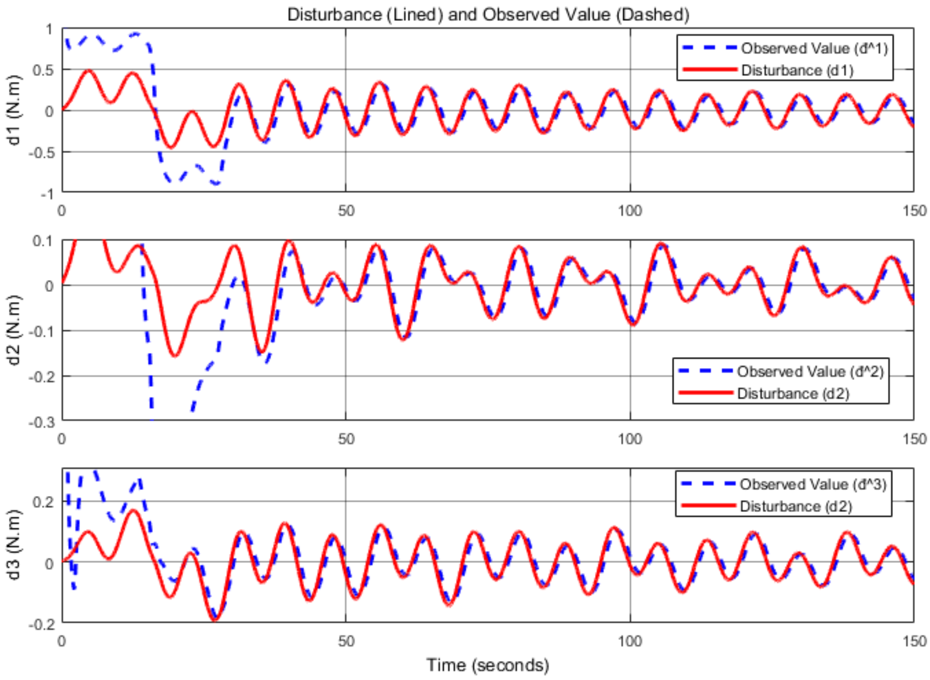

Fig. 4 Time responses of total disturbance and its observed value

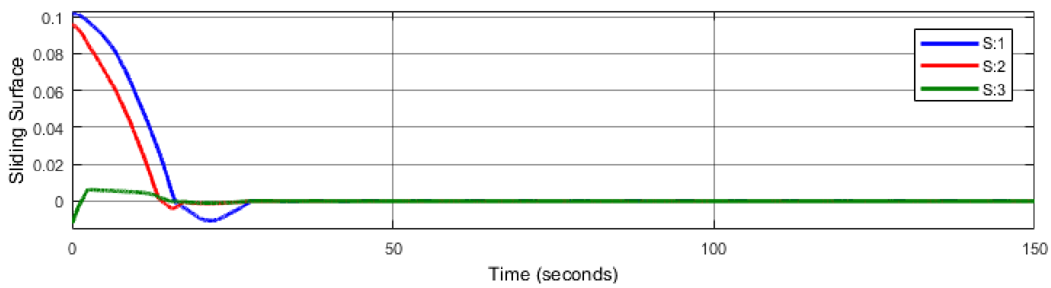

Fig. 5 Time response of sliding surface

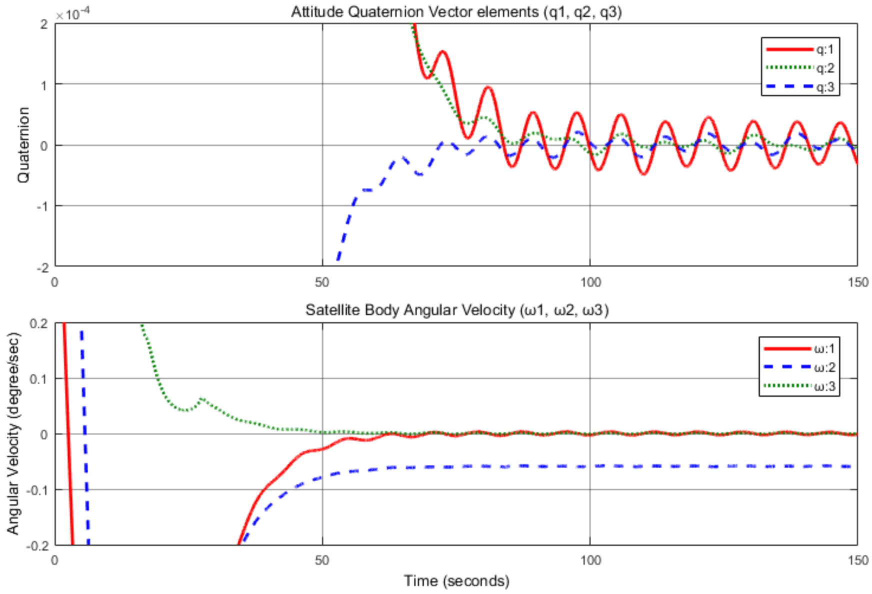

Fig. 6 Time responses of system states in presence of DOBC

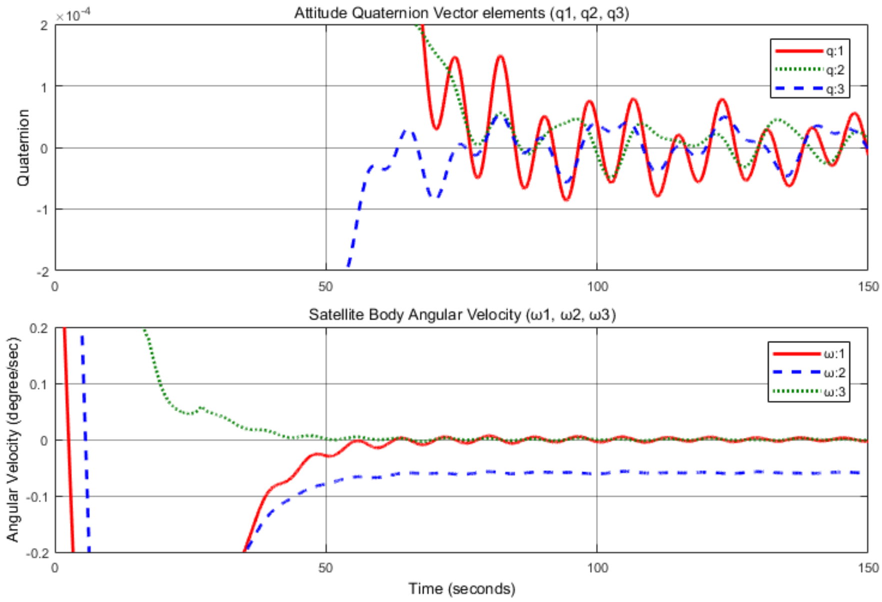

Fig. 7 Time responses of system states suffering lack of DOBC

4.3 Lack of DOBC effects

In this subsection, the effect of the DOBC part of controller $\hat{d}$ is examined. As mentioned, Fig. 2 indicates the overall performance of presented ACS, but for perceiving the effect of DOBC, should have a more precise look at results. However, in the case of disconnection of the disturbance observer control part from controller, system accuracy become less. Fig. 6 indicates

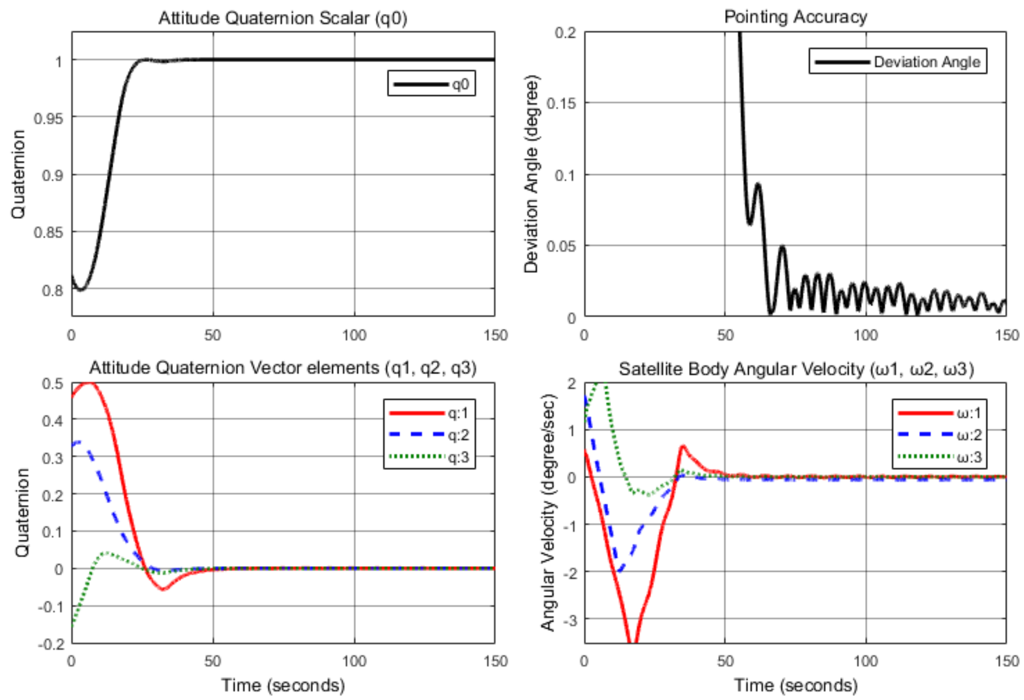

Fig. 8 Time responce of composite DOBC- H∞ control scheme

quaternion and angular velocity while profit by DOBC scheme against in Fig. 7 that does not use it.

In fact, the reduced accuracy in the control performance, due to the omission of DOBC, may about ten times; but cannot impair the stability of the overall control line of action. This shown the power of introduced SMC in this article.

4.4 Attitude stabilization by other composite control scheme

In comparison to another control schemes, confirming the ability of DOBC, proportional derivative (PD) controller (9) and H-infinity controller (10) are selected as nominal controller to join with considered DOBC scheme, deliberately.

Based on simulations, these controllers could not stabilize presented ACS, solitarily. While a composite scheme control including presented nominal controllers and DOBC can do it as well and behavior of system states in Fig. 8 and Fig. 9 show validity of this assertion.

5. Closing

5.1 Conclusion

In this work, a spacecraft attitude control system that suffer from vibration torques (elastic appendages) and actuator failure, is introduced. A disturbance observer based anti-disturbance fault tolerant control for flexible satellite for utilization of faulty actuator components and improving the pointing accuracy in the absence of the anti-vibration equipment, are designed. Simulation results for several feedback controllers with/without disturbance observer, are conducted. These

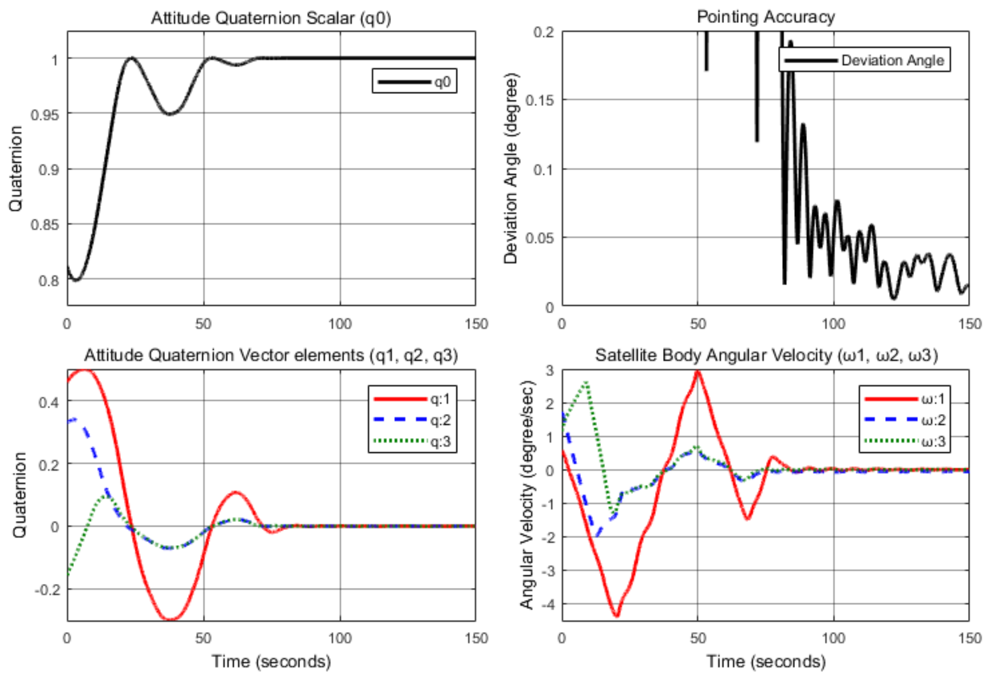

Fig. 9 Time responce of composite DOBC-PD control scheme

simulations indicate that the control system design based on the introduced composite compensation mechanism are promising technique.

5.2 Future study

In previous research Yadegari, Chao and Yukai (2016), a rigid satellite model has been used to show that the pure SMC approach provides more robust performance against the uncertainties than some previous results in presence of faulty reaction wheel actuators. However, it was also pointed out that when the ACS has some deficiencies in the actuator system, the result is unsatisfactory. This work focused on employing DOBC scheme along with SMC, for flexible appendage effects reduction. In future investigation, to improve previous work, we will try improved disturbance observers and nominal controllers to decrease time to obtain stability in more difficult conditions.

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