Composite Attitude Control for Flexible Spacecraft with Simultaneous Disturbance Attenuation and Rejection Performance*

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Abstract: In this paper, a composite attitude control approach for orbiting spacecraft with rigid central hubs and flexible appendages is presented. The established attitude control model consists of the vibration modes excited by the rigid body, the space environment disturbances, the measurement noises, and the model uncertainty. The model is formulated into a dynamic system with two types of disturbance inputs. A composite control law with the simultaneous disturbance attenuation and rejection performance is presented for the flexible spacecraft system subject to multiple disturbances. The disturbance-observer-based control is designed for feedforward compensation of the elastic vibration. The H_∞ state-feedback controller is designed to perform the robust attitude control in the presence of the space environment disturbances, measurement noises, and the model uncertainty. Numerical simulations show that the performance of the attitude control systems can be improved by combining the disturbance observer with H_∞ state-feedback control.

Keywords: flexible spacecraft; attitude control; disturbance-observer-based control; H_∞ control; multiple disturbance; vibration control; anti-disturbance control; composite hierarchical anti-disturbance control

1. Introduction

Flexible spacecraft have played an increasingly important role in space missions. To reduce launch costs, lightweight materials are applied to the spacecraft structure, which may lead to low-frequency elastic modes. The unwanted excitation of the flexible modes will deteriorate the pointing and stability performance of attitude control systems (ACSs). This situation arises because flexible spacecraft structures are usually coupled systems of elastically deformable bodies whose behaviour is characterized by non homogeneous equations with uncertain parameters. The dynamical model of spacecraft is non-linear and its inertia matrix and elastic modes are usually unknown exactly, so the parametric uncertainty should be taken into account. Moreover, space environmental disturbances

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also may degrade the pointing accuracy and stability of the spacecraft. Therefore, the fundamental attitude of the control design problem for flexible spacecraft is to overcome the influence of vibration, together with the model uncertainty, unmodelled dynamics, the space environment disturbances, and measurement noise.

In recent decades, the proportional-integral-derivative (PID) controller has been widely applied in ACS design, due to its simplicity and reliability[1, 2]. When model uncertainties exist or external disturbance varies, it is difficult to achieve satisfactory PID control performance. New design schemes are required for the simultaneous attitude control and vibration suppression. Optimal control of flexible spacecraft has been considered in references [3, 4], but in general this solution requires a high-order controller, which is not acceptable in the case of an onboard computer where memory is very limited. Variable structure control and sliding mode control, known to be efficient control strategies for systems with strong non-linearity and modelling uncertainty, have also been applied to ACS design by combining with active vibration control via piezoelectric actuators[5-7]. It is noted that a possible chattering phenomenon resulting from variable structure control and sliding mode control has an inevitable effect on the steady-state precision.

In modern control theory, disturbance attenuation and rejection is a fundamental problem since the model uncertainty, unmodelled dynamics, and even non-linearities can be described as an equivalent disturbance input, besides various noises and disturbances. In the presence of external disturbance and model uncertainty, robust control theory provides designers with a systematic approach for analysis and synthesis of the whole system. In paper [8], the robust control is investigated for the influence of the flexibility on the rigid motion, the presence of disturbances acting on the structure, and parameter variations. It is noted that H_∞ controllers have demonstrated their effectiveness in on-orbit attitude control experiments for Engineering Test Satellites ETS-VI and ETS-VIII[9, 10]. Furthermore, a feasible mixed H_2/H_∞ controller has been designed for rigid spacecraft[11]. In reference [12], an H_∞ multi-objective controller based on the linear matrix inequality (LMI) framework was designed for flexible spacecraft. H_∞ control can provide satisfactory disturbance attenuation performance, but it is of limited usefulness for attitude control and active vibration control problems since the characteristics of the disturbance are neglected.

To overcome the conservativeness of H_∞ control approaches, disturbance-observer-based control, or DOBC, has received extensive attention for many practical plants[13, 14]. A survey can be seen in paper [15] for non-linear DOBC. Compensation through feedforward for the modelling error or the exogenous disturbance has been considered as a robust control scheme when the error or disturbance can be estimated. In references [16, 17], DOBC for non-linear robotic manipulator was investigated in the presence of constant and harmonic disturbances. In paper [13], the DOBC approach in a state space framework was presented for a class of non-linear systems, where the disturbance was generated by a linear exogenous system. Other recent developments can be seen in references [18-20]. Although DOBC can provide elegant disturbance rejection performance, the obstacle to DOBC is that the dynamics of the disturbance estimation error rely on strict confinement of the disturbance and plant model.

Anti-disturbance control methodologies can be divided into two main types. One is the disturbance attenuation method (such as H_∞ control) where the influence of the disturbance can be decreased for the reference output. The other is the disturbance rejection method which can realize compensation of the disturbance with internal mode controllers or adaptive compensation controllers. However, these approaches only deal with one type of disturbance. In practice, together with the rapid development on sensor and data processing technologies, the disturbances or noise from different sources (e. g. sensor and actuator noise, friction, vibration, etc.) can be characterized by different mathematical models. Also, disturbance can represent the unmodelled dynamics and system uncertainties. For the case of multiple disturbances, a composite hierarchical anti-disturbance control was proposed[21, 22] to guarantee the simultaneous disturbance attenuation and rejection performance. However, the disturbances rejected in these two references are confined to be an exosystem with known parameters, which cannot be used for the attitude and vibration control problems studied in this paper.

In this paper, a composite attitude controller design approach is designed for flexible spacecraft based on DOBC and H_∞ state-feedback control. DOBC can reject the effect of vibrations from flexible appendages, and H_∞ state-feedback control can attenuate the influence of the norm bounded disturbances, and correspondingly guarantee the robust stability against other disturbances and model uncertainty. Simulations of flexible spacecraft show that the performance of ACSs can be improved with comparisons to H_∞ state-feedback control.

The remainder of this paper is organized as follows. In Section 2, the dynamic model of the flexible spacecraft is introduced. In Section 3, the stabilization of the system under the given controller is analysed, and the solution of the controller is resolved. In Section 4, the effectiveness of the proposed control algorithm is confirmed by numerical simulations. Conclusions are provided in Section 5. In the following, if not otherwise stated, matrices are assumed to have compatible dimensions. The identity and zero matrices are denoted by I and 0, respectively, with appropriate dimensions. For a square matrix M, $\mathrm{sym}(M)=M+M^T$ is denoted. For a symmetric matrix M, the notation $M>(\geqslant 0)$ is used to denote that it is positive definite (positive semi-definite). The case for $M<(\leqslant 0)$ follows similarly. The norms $\|\cdot\|$ of a real vector function and a matrix are defined as their Euclidean norms.

2. Problem Formulation

Similarly to references [5, 8], the single-axis model can be derived from the non-linear attitude dynamics of the flexible spacecraft. In this paper, the problem is simplified and only considers the single-axis rotational manoeuvre. It is assumed that this model includes one rigid body and one flexible appendage (see Fig. 1), and the relative elastic spacecraft model is described as

$$J\ddot{\theta}+F\ddot{\eta}=u+w \tag{1}$$

$$\ddot{\eta}+2\xi\omega\dot{\eta}+\omega^2\eta+F^T\ddot{\theta}=0 \tag{2}$$

where θ is the attitude angle, J is the spacecraft inertia, F is the modal participation matrix, u is the control torque, w represents the merged disturbance including the space environmental disturbances, moment-of-inertia uncertainty, and noises from sensors and actuators, η is the flexible modal coordinate, ξ is the damping ratio, and ω is the modal frequency. Combining (1) with

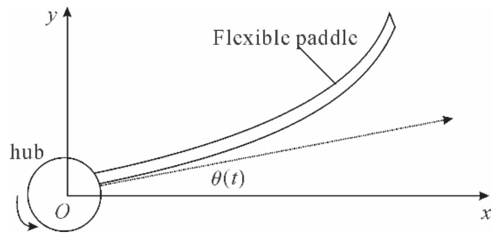


Fig. 1 Spacecraft with flexible appendages

(2) yields

$$(J-FF^T)\ddot{\theta}=F(2\xi\omega\dot{\eta}+\omega^2\eta)+u+w \tag{3}$$

In (3), $F(2\xi\omega\dot{\eta}+\omega^2\eta)$ is caused by the flexible appendages and can be modelled as the disturbance. Denoting

$$x(t)=[\theta(t),\dot{\theta}(t)]^T$$

then (3) can be transformed into

$$\dot{x}(t)=A_0x(t)+\{B_u u(t)+B_f d_0(t)+B_d d_1(t)\} \tag{4}$$

where the coefficient matrices are

$$A_0=\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix};\ B_u=B_f=B_d=\begin{bmatrix}0\\ (J-FF^T)^{-1}\end{bmatrix}$$

In this paper, $d_0(t)=F(2\xi\omega\dot{\eta}+\omega^2\eta)$ is the disturbance to represent the flexible appendages; $d_1(t)$ represents the merged disturbance from space environmental disturbances, moment-of-inertia uncertainty, and noises from sensors and actuators.

According to the practical situations, it can be supposed that $\|\dot{d}_0(t)\|\leqslant W_0$ and $\|d_1(t)\|\leqslant W_1$, where W_0 and W_1 are known positive constants.

The reference output equation of the system for the H_∞ performance index is defined as $z(f)=C_1x(t)$. Then, the system model can be described by

$$\begin{cases}\dot{x}(t)=A_0x(t)+B_u u(t)+B_f d_0(t)+B_d d_1(t)\\ z(t)=C_1x(t)\end{cases} \tag{5}$$

where $u(t)$ and $z(t)$ are the control input and the output, respectively.

As state feedback controller has been widely applied in many practical systems, a direct application of state feedback control strategy would lead to

$$u_c(t)=Kx(t)$$

where K are control gains to be determined. Our aim is to design state feedback controllers for (5) such that the closed-loop system is asymptotically stable with the guaranteed generalized H_∞ performance, where the generalized H_∞ performance is defined as

$$J_\infty:=\|z(t)\|^2-\gamma^2\|d_1(t)\|^2$$

Different from previous works such as references [3, 5, 8], the dynamic model for the flexible spacecraft includes two types of disturbances which describe the vibration modes excited by the rigid body, the space environment disturbances, the measurement noise, and the model uncertainty respectively. Both DOBC and H_∞ control are used to enhance the anti-disturbance performance, compared with PID-type atlitude control laws[2]. In the following, the composite anti-disturbance control approach presented recently in papers [21, 22] will be generalized to the considered attitude control problem. To solve the attitude and vibration control problem, a different type of disturbance $d_0(t)$ which satisfies $\|d_0(t)\| \leqslant W_0$ is considered, while in papers [21, 22], the disturbance to be rejected is described by an exosystem with known parameters.

3. Composite Attitude Controller Design

3.1 Disturbance Observer Design

According to system (5), the disturbance observer is formulated as

$$\begin{cases} \dot{\tau}(t) = -N(x)B_f(\tau + p(x)) - N(x)(A_0 x(t) + B_u u(t)) \\ \hat{d}_0 = \tau + p(x) \end{cases} \tag{6}$$

where $N(x)$ is the gain of the observer, defined by

$$N(x) = \frac{\partial p(x)}{\partial x}$$

Here, $N(x)$ is a constant, and is abbreviated by N. The error of disturbance observer is defined as

$$e(t) = d_0(t) - \hat{d}_0(t)$$

Then

$$\dot{e}(t) = \dot{d}_0 - NB_f e(t) - NB_d d_1(t) \tag{7}$$

According to the practical situation of the flexible appendages, here, we should design an appropriate N to make $e(t) \to 0$.

In the DOBC scheme, the controller can be constructed as $u(t) = -\hat{d}_0(t) + u_c(t)$, which is directly described by Fig. 2 (where $\hat{d}_0(t)$ is the estimation of $d_0(t)$). It is shown that the composite attitude controller possesses the hierarchical architecture. In fact, it has two loops: the inner loop is used to estimate the vibration and compensate it, while the outer loop provides the H_∞ control to attenuate the norm bounded disturbances. After the above transformations, it is possible to deal with the parameter design by adopting the popular robust control techniques.

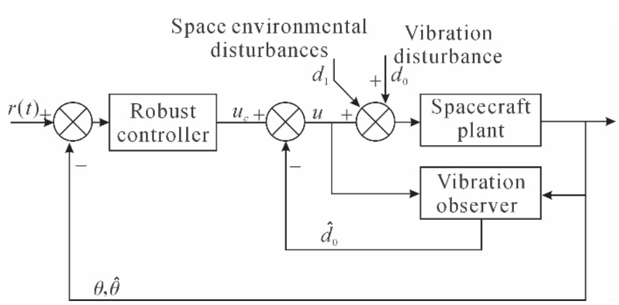


Fig. 2 Composite controller design

Substituting $u(t)$ to (5) and (7), it is possible to obtain the augmented system

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A_0 + B_u K & B_f \\ 0 & -NB_f \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} 0 & B_d \\ I & -NB_d \end{bmatrix} \begin{bmatrix} \dot{d}_0(t) \\ d_1(t) \end{bmatrix} \tag{8}$$

Denoting $\bar{x} = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$

$$\begin{cases} A = \begin{bmatrix} A_0 + B_u K & B_f \\ 0 & -NB_f \end{bmatrix}, & d(t) = \begin{bmatrix} \dot{d}_0(t) \\ d_1(t) \end{bmatrix} \\ B = \begin{bmatrix} 0 & B_d \\ I & -NB_d \end{bmatrix}, & C = [C_1 \quad C_2] \end{cases} \tag{9}$$

For $\dot{d}_0(t)$ and $d_1(t)$ are all bounded, then $d(t)$ is bounded also, thus, (8) and its reference output equation in the H_∞ performance index can be described as

$$\begin{cases} \dot{\bar{x}}(t) = A\bar{x}(t) + Bd(t) \\ z(t) = C\bar{x}(t) \end{cases} \tag{10}$$

3.2 Stability of the Composite Systems

In this section, the stability of the composite system is proved, and the parameters of the composite controller can be given via the solution of a class of linear matrix inequalities (LMIs).

Theorem 1

To system (8), for $\gamma > 0$, if there exists symmetrical matrix $Q_1 > 0$, $P_2. > 0$, R_1, and R_2 that satisfies

$$\begin{bmatrix} \Phi_{11} & Q_1 C_1^T & 0 & B_d & B_f \\ * & -\gamma I & 0 & 0 & C_2 \\ * & * & -\gamma I & 0 & P_2 \\ * & * & * & -\gamma I & -B_d^T R_2^T \\ * & * & * & * & \Phi_{55} \end{bmatrix} < 0 \tag{11}$$

where

$$\Phi_{11} = \mathrm{sym}(A_0 Q_1 + B_u R_1)$$
$$\Phi_{55} = \mathrm{sym}(-R_2 B_f)$$

then system (8) is asymptotically stable and satisfies H_∞ performance, and the controller gain is given by $K = R_1 Q_1^{-1}$ and the observer gain is given by $N = P_2^{-1} R_2$

Proof

Based on the bounded real lemma, the system (10) satisfies H_∞ performance $\|z\| < \gamma \|d(t)\|$, if there exists symmetrical matrix $P > 0$ and $\gamma > 0$ satisfying (see for example[13])

$$\begin{bmatrix} A^T P + PA & PB & C^T \\ B^T P & -\gamma I & 0 \\ C & 0 & -\gamma I \end{bmatrix} < 0 \tag{12}$$

Substituting (9) into (12), and denoting

$$P = \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}$$

we can get

$$\begin{bmatrix} \Theta_{11} & P_1 B_f & 0 & P_1 B_d & C_1^T \\ * & \Theta_{22} & P_2 & -P_2 N B_d & C_2^T \\ * & * & -\gamma I & 0 & 0 \\ * & * & * & -\gamma I & 0 \\ * & * & * & * & -\gamma I \end{bmatrix} < 0 \quad (13)$$

where

$$\Theta_{11} = \mathrm{sym}(P_1 P_0 + P_1 B_u K)$$
$$\Theta_{22} = \mathrm{sym}(-P_2 N B_f)$$

From (13), by some matrix transformations, it is possible to obtain

$$\begin{bmatrix} \Theta_{11} & C_1^T & 0 & P_1 B_d & P_1 B_f \\ * & -\gamma I & 0 & 0 & C_2 \\ * & * & -\gamma I & 0 & P_2 \\ * & * & * & -\gamma I & -B_d^T N^T P_2 \\ * & * & * & * & 0 \\ * & * & * & * & \Theta_{22} \end{bmatrix} < 0 \quad (14)$$

Denoting

$$Q = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix} = \begin{bmatrix} P_1^{-1} & 0 \\ 0 & P_2^{-1} \end{bmatrix} = P^{-1}$$
$$R_1 = KQ_1, R_2 = P_2 N$$

then pre-multiplying diag$\{Q_1, I, I, I, I\}$ and post-multiplying diag$\{Q_1, I, I, I, I\}$ to the left and right side of the matrix of (14), it is possible to obtain the conclusion.

4. Simulations

4.1 Simulation Parameter

In order to demonstrate the effectiveness of the proposed control algorithm, numerical simulations will be performed in this section. The composite control scheme will be applied to a spacecraft with one flexible appendage. Since low-frequency modes are generally dominant in a flexible system, only the lowest two bending modes have been considered for the implemented spacecraft model.

We suppose that $\omega_1 = 1.27$ and $\omega_2 = 6.58$ with damping $\xi_1 = 0.004\ 705$ and $\xi_2 = 0.005\ 590$ respectively. As an example, this paper tries to control the attitude in the pitch channel, where $J = 35.72\ \mathrm{kg\cdot m^2}$ (J is the nominal principal moment of inertia of pitch axis). In addition, 35 percent perturbation of the nominal moment of inertia will also be considered.

The flexible spacecraft is designed to move in a circular orbit with the altitude of 500 km, then the orbit rate $n = 0.0011$ rad/s, The disturbance torques acting on the satellite are assumed as follows

$$\begin{cases} T_{dx} = 5.2 \times 10^{-5}(3\cos nt + 1) \\ T_{dy} = 5.2 \times 10^{-5}(3\cos nt + 1.5\sin nt) \\ T_{dz} = 5.2 \times 10^{-5}(3\sin nt + 1) \end{cases}$$

The initial pitch attitude of the spacecraft is $\theta=0.08$ rad, and $\dot{\theta}=0.0006$ rad/s. $F(2\xi\omega\dot{\eta}+\omega^2\eta)$ is defined as vibration torque which comes from the flexible appendages.

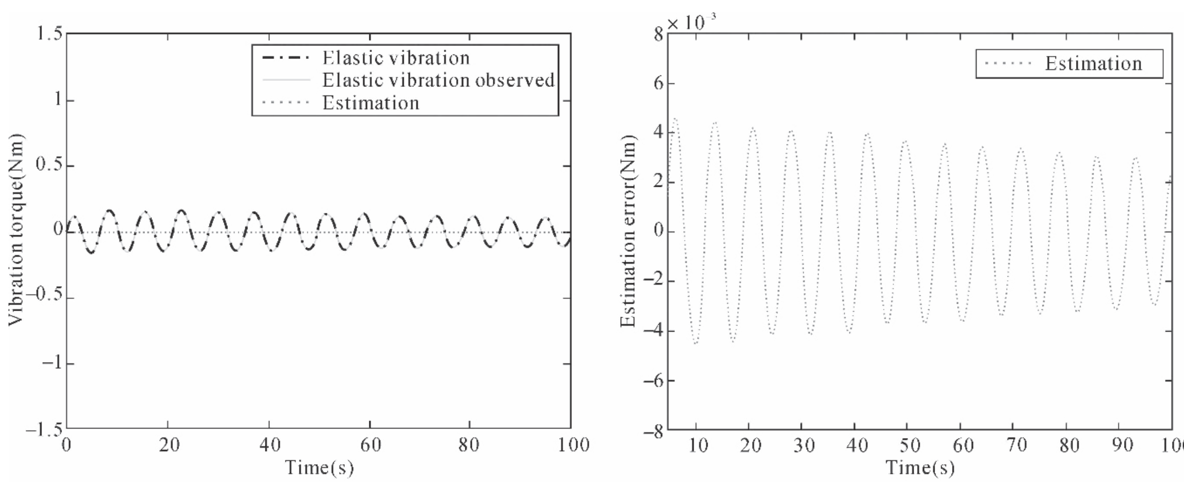
Selecting $\gamma=5.7$, it is possible to obtain the anticipated controller gain

$$K=[-67.85 \quad -65.5]$$

and the observer gain $N=[0\ 1000]$.

4.2 Simulation Analysis

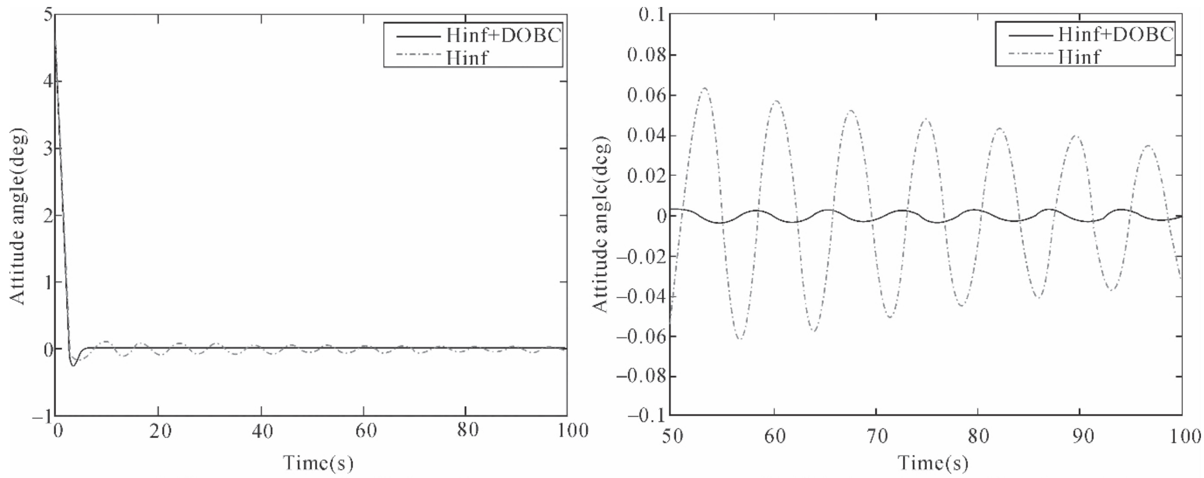
Fig. 3(a) shows the elastic vibration, its estimation, and the estimation error respectively. The estimation error is amplified in Fig. 3(b), where one can see that satisfactory tracking performance can be achieved for the vibration from the flexible appendages. With the estimation, the effect of the elastic vibration can be rejected by feed-forward compensation. In Fig. 4(a), the attitude angle of the spacecraft is demonstrated and compared with the pure H_∞ attitude control. Fig. 4(b) is the amplification of Fig. 4(a), where one can see that the improved response performance can be guaranteed under the composite controller. Correspondingly, Fig. 5(a) and (b) show that the attitude stabilization can also be improved with a composite controller in the presence of flexible vibration. In addition, + 35 per cent perturbation of the nominal moment of inertia is also considered. Fig. 6 shows that the proposed controller has improved robustness against model uncertainty, when compared with H_∞ control.



(a) Time responses of vibration and vibration observed (b) Estimation error zoom of the above plot

Fig. 3 Vibration estimation error in disturbance observer

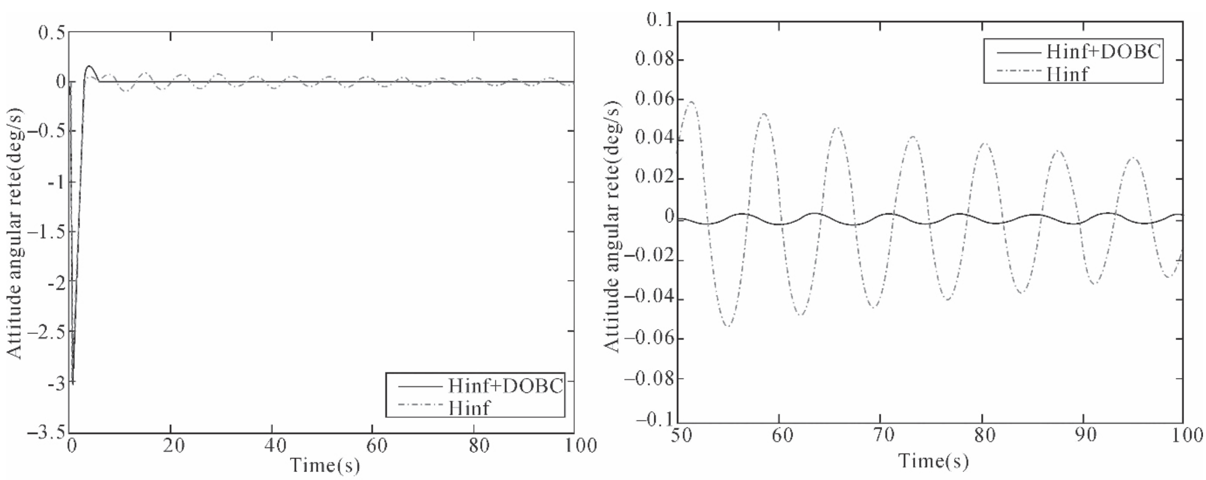
From the simulations, it can be seen that the composite controller based on DOBC and H_∞ control is capable of compensating the effect of the elastic vibration actively, and can improve the pointing precision and stabilization of the flexible spacecraft in the presence of the model uncertainty and space environmental disturbances.



(a)Time responses of attitude angle

(b)Attitude angle zoom of the above plot

Fig. 4 Time responses of attitude angle



(a) Time responses of attitude angular velocity

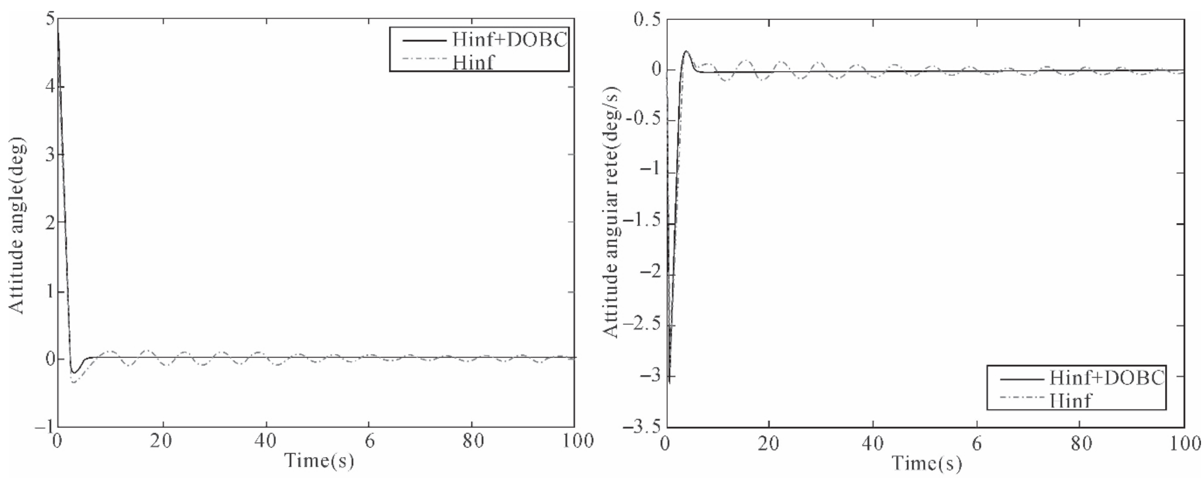
(b) Attitude angle zoom of the above plot

Fig. 5 Time responses of attitude angular velocity

5. Conclusions

In this paper, a composite attitude control scheme for flexible spacecraft is presented in the presence of model uncertainty, elastic vibration, and space environmental disturbances. The proposed composite controller possesses a hierarchical architecture, which consists of DOBC in the inner loop and H_∞ control in the outer loop. DOBC can reject the effect of the elastic vibration from the flexible appendages, and H_∞ control can attenuate the effect of the model uncertainty, noise from sensors, and external disturbances. Numerical simulations have shown that the composite controller can enhance the pointing accuracy and stabilization of the flexible spacecraft. This provides a promising and simple attitude control technique for flexible spacecraft.

It is noted that only H_∞ state feedback control is considered in this paper. A next step will attempt to use H_∞ output feedback control for more general cases. For the output feedback controllers, it is expected that the observer for the state could be designed together with the disturbance observer, similarly to the so-called full-order observer design discussed in reference [13]. Another point is that this paper has only considered two types of disturbance and has supposed that $d_1(t)$ and the derivative of $d_0(t)$ are bounded respectively. Although numerical simulations have shown that enhanced robustness can be achieved by using the proposed method, more general theoretical research and experimental simulations need to be carried out in the future.



(a) Time responses attitude angle

(b) Time responses of attitude angular velocity

Fig. 6 Time responses of spacecraft attitude under inertia perturbation

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