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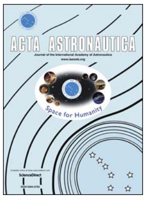

Research paper

Attitude stabilization of flexible spacecrafts via extended disturbance observer based controller

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ABSTRACT

To achieve the high-precision attitude stabilization for the flexible spacecraft in the presence of space environmental disturbances, unmodeled dynamics, and the disturbances caused by the elastic vibration of flexible appendages, an extended disturbance observer (EDO) based controller is proposed. The proposed controller is formulated by combining EDO and a backstepping feedback controller. EDO is used to estimate the disturbance, which is modeled as an unknown high-order differentiable equation and the rth-order derivative of the disturbance is assumed to be bounded. Compared to the conventional first-order disturbance observer, the higher order EDO offers improvement in estimate accuracy, if the absolute values of poles for EDO transfer function are chosen larger than the frequency content of the disturbance. Then, the output of EDO plus the backstepping feedback controller are applied to stabilize the attitude with high precision by rejecting disturbances for the flexible spacecraft. Finally, numerical simulations have been conducted to verify the effectiveness of the proposed controller.

1. Introduction

The flexible spacecraft is characterized by a central rigid body with attached appendages such as antennae and solar panels. With the increasing requirements of spacecraft functions, the structure of these appendages will be more complex. However, the disturbances caused by the elastic vibration of flexible appendages can considerably deteriorate the control performance and even lead to system instability for the flexible spacecraft. Moreover, space environmental disturbances and parameter uncertainties also decrease the accuracy of flexible spacecraft attitude control. To achieve the high-precision attitude control, the control scheme should be able to overcome the effects of space environmental disturbances, parameter uncertainties, and vibration of flexible appendages, simultaneously. Thus, a number of control methods have been developed including but not limited to adaptive control [1], sliding mode control [2], H_∞ control [3], and disturbance observer based control (DOBC). DOBC is one of the promising methods for its high disturbance rejection ability and simple structure [4,5].

There have been plenty of researches on DOBC, such as linear DOBC [6], nonlinear DOBC [7–14], and composite hierarchical anti-disturbance control for the plant with multiple disturbances [15–23]. Recently, DOBC was applied to address the problem of attitude control for the flexible spacecraft [24–27]. In [24,25], the flexible spacecraft was modeled as a rigid body with two types of disturbances. One was the vibration of the flexible appendage, which was assumed to be a derivative-bounded disturbance. Another was the “equivalent disturbance” including space environmental disturbances and system uncertainties, which was assumed to be a norm-bounded disturbance. Then a conventional first-order nonlinear disturbance observer was used to compensate the vibration of flexible appendages, and a state-feedback controller was applied to suppress the “equivalent disturbance” and the estimate error of the disturbance observer. Furthermore, the input time delay was considered in the controller design in [26,27]. However, the conventional first-order disturbance observer is difficult to precisely estimate the disturbance caused by the elastic vibration of flexible spacecraft since the disturbance is characterized by the high-order dynamics, thus decreasing the accuracy of attitude control for the flexible spacecraft.

The performance of DOBC depends greatly on the accuracy of the disturbance estimate. Thus, various results on the design of the disturbance observer have appeared in literature. In general, the disturbance observer can be designed either in the state space domain or in the transfer function domain [28]. Since the state space allows the transient behavior analysis, many studies have been conducted in the state space domain, such as the nonlinear disturbance observer for constant disturbances [7,8] and harmonic disturbances [10,11]. Moreover, the sliding mode control, fuzzy control, and neural network control methods were introduced to the design of the disturbance

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observer [29–31]. Note that the high-order dynamics of the disturbance is considered in the design of the full-order observers, such as integral observer [32], proportional integral observer [33], generalized proportional integral observer [34], generalized extended state observer [35], but there is no need to estimate the system states when all system states are available [11]. Hence, only the reduced-order observer (i.e., disturbance observer) is required to estimate the disturbance. Therefore, the structure of the disturbance observer is simpler than that of the full-order observer. Recently, the generalized disturbance observer was presented to estimate the high-order disturbance in the form of time series expansion [36]. Then a nonlinear function was introduced to improve the performance of the generalized disturbance observer [37]. Afterwards, an extended disturbance observer (EDO) was used for the high-order system with mismatched uncertainties [38], where the type of disturbance estimated by EDO includes the special case of the type of disturbance in [36,37]. However, the efforts of different orders on the performance of EDO were not investigated.

In this paper, an extended disturbance observer based control (EDOBC) scheme is proposed to stabilize the attitude with high precision for the flexible spacecraft. Similar to the research for the mismatched uncertain systems in [38], a type of EDO is designed to estimate the total disturbance for the flexible spacecraft attitude stabilization. The total disturbance, including the vibration of flexible appendages, unmodeled dynamics, and space environmental disturbances, is modeled as an unknown high-order differentiable equation, and the rth-order derivative of the disturbance is assumed to be bounded. Different from the work of [38], the efforts of different orders on the performance of EDO are investigated. Performance analysis shows that the higher order EDO offers better estimate accuracy as compared to the conventional first-order disturbance observer, if the absolute values of poles for EDO transfer function are chosen larger than the frequency content of the disturbance. Then, the output of EDO plus the backstepping feedback controller are applied to achieve the high-precision attitude stabilization of the flexible spacecraft. The global stability of the entire system can be guaranteed since the proposed controller is designed via the backstepping design procedures.

The rest of this paper is organized as follows: Section 2 summarizes the spacecraft attitude dynamics and structure of the proposed controller. EDO and its performance analysis are given in Section 3. Section 4 presents EDOBC and simulation results are presented in Section 5. Finally, the conclusion is given in Section 6.

2. Spacecraft attitude dynamics and controller structure

2.1. Spacecraft attitude dynamics

In this paper, let $\boldsymbol{\omega}$ denote the angular velocity of the spacecraft with respect to the inertial frame and then the equations of motion for the flexible spacecraft can be described in the body-fixed frame as [39,40]

$$J\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times}(J\boldsymbol{\omega} + \boldsymbol{\delta}^{T}\dot{\boldsymbol{\eta}}) - \boldsymbol{\delta}^{T}\ddot{\boldsymbol{\eta}} + \boldsymbol{u} + \boldsymbol{d}_{0} \tag{1}$$

$$\ddot{\boldsymbol{\eta}} + C\dot{\boldsymbol{\eta}} + K\boldsymbol{\eta} + \boldsymbol{\delta}\dot{\boldsymbol{\omega}} = 0 \tag{2}$$

where J and u denote the inertia matrix and control torque, respectively; d_0 denotes the space environmental disturbances and unmodeled dynamics; $\boldsymbol{\delta}$ denotes the flexible coupling matrix; $\boldsymbol{\eta}$ denotes the modal coordinate vector; $\boldsymbol{K} = diag(\zeta_1^2, \ldots, \zeta_n^2)$ denotes the stiffness matrix; ζ denotes the natural frequency; $\boldsymbol{C} = diag(2\xi_1\zeta_1, \ldots, 2\xi_1\zeta_n)$ denotes the damping matrix; ξ denotes the associated damping; $(\cdot)^{\times}$ denotes a skew symmetric matrix constructed by 3 elements of $(\cdot)$.

Define the total disturbance as $\boldsymbol{d} = -\boldsymbol{\omega}^{\times}\boldsymbol{\delta}^{T}\dot{\boldsymbol{\eta}} - \boldsymbol{\delta}^{T}\ddot{\boldsymbol{\eta}} + \boldsymbol{d}_0$. Then the flexible spacecraft dynamics can be simplified as

$$J\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times}J\boldsymbol{\omega} + \boldsymbol{u} + \boldsymbol{d} \tag{3}$$

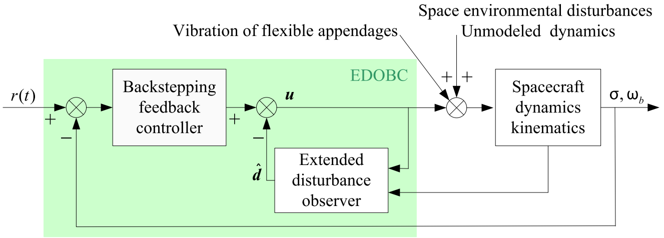

Fig. 1. Block diagram of EDOBC.

Let the spacecraft attitude be represented by the modified Rodrigues parameter (MRP). The equations of motion for the flexible spacecraft can be described as

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{F}(\boldsymbol{\sigma})\boldsymbol{\omega}_b \tag{4}$$

where $\boldsymbol{\sigma}$ denotes the MRP representation for spacecraft attitude in the body-fixed frame with respect to the orbit frame; $\boldsymbol{F}(\boldsymbol{\sigma}) = 0.25(1 - \|\boldsymbol{\sigma}\|_2^2)\boldsymbol{E}_3 + 0.5\boldsymbol{\sigma}^{\times} + 0.5\boldsymbol{\sigma}\boldsymbol{\sigma}^{T}$; $\|\cdot\|_2$ denotes the 2-norm of vector $(\cdot)$; $\boldsymbol{E}_3$ denotes the 3×3 identity matrix; $\boldsymbol{\omega}_b = \boldsymbol{\omega} - C_o^b\boldsymbol{\omega}_o$ denotes the angular velocity of the body-fixed frame with respect to the orbit frame; $\boldsymbol{\omega}_o$ denotes the angular velocity of the orbit frame with respect to the inertial frame; C_o^b denotes the rotation matrix describing a rotation from the orbit-fixed frame to the body-fixed frame.

2.2. Structure of the proposed controller

The objective of this study is to design an EDOBC scheme to stabilize the attitude with high precision for the flexible spacecraft system (3) and (4). The structure of EDOBC can be described by Fig. 1. As shown in Fig. 1, EDOBC is formulated by combining EDO and a backstepping feedback controller. EDO is applied to compensate the effects of the vibration of flexible appendages, unmodeled dynamics, and space environmental disturbances, simultaneously. Then, the output of EDO plus the backstepping feedback controller are applied to achieve the high-precision attitude stabilization for the flexible spacecraft.

3. Extended disturbance observer design and analysis

In this section, the model of the total disturbance is given first. Then, similar to the research for the mismatched uncertain systems in [38], EDO is designed to estimate the total disturbance for the flexible spacecraft attitude stabilization. Finally, the efforts of different orders on the performance of EDO are investigated.

3.1. Disturbance model

The disturbance torque caused by the elastic vibration of flexible spacecraft is characterized by the high-order dynamics. However, it is difficult to obtain the frequency of vibration and the exact value of the disturbance in engineering practices. Thus, by taking the vibration of flexible appendages, unmodeled dynamics, and space environmental disturbances into consideration simultaneously, it is reasonable to assume that the total disturbance satisfies $\|\boldsymbol{d}^{(j)}\|_2 \le \gamma$, $\gamma > 0$, $j = 0, 1, 2, \ldots, r$. The only requirement for the disturbance considered in this study is that the jth-order derivative of the disturbance is bounded. Obviously, this type of disturbance generalizes the disturbance types considered in previous studies. Compared to the conventional low-order disturbance model in previous studies, the high-order disturbance model is more accurate to describe the exact value of the disturbance for flexible spacecraft.

By defining $x_1 = \boldsymbol{d}$, $x_2 = \dot{\boldsymbol{d}}$, $x_3 = \ddot{\boldsymbol{d}}$, …, and $\boldsymbol{x}_r = \boldsymbol{d}^{(r-1)}$, the total disturbance can be described in the state space as follows