Chinese Journal of Aeronautics, 2013,**26**(3): 687–696

Chinese Society of Aeronautics and Astronautics & Beihang University
Chinese Journal of Aeronautics
cja@buaa.edu.cn
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Composite control method for stabilizing spacecraft attitude in terms of Rodrigues parameters

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Received 9 January 2012; revised 13 February 2012; accepted 5 March 2012
Available online 30 April 2013

KEYWORDS
Attitude control;
Composite control;
Disturbance observer;
Finite time control law;
Spacecraft

Abstract In this paper, the attitude stabilization problem of a rigid spacecraft described by Rodrigues parameters is investigated via a composite control strategy, which combines a feedback control law designed by a finite time control technique with a feedforward compensator based on a linear disturbance observer (DOB) method. By choosing a suitable coordinate transformation, the spacecraft dynamics can be divided into three second-order subsystems. Each subsystem includes a certain part and an uncertain part. By using the finite time control technique, a continuous finite time controller is designed for the certain part. The uncertain part is considered to be a lumped disturbance, which is estimated by a DOB, and a corresponding feedforward design is then implemented to compensate the disturbance. Simulation results are employed to confirm the effectiveness of the proposed approach.

1. Introduction

The attitude control of spacecraft is one of the fundamental aeronautical control problems, which has attracted strong attention in recent years. Many nonlinear approaches have been proposed to solve the attitude control problem, including passivity-based control,[1] adaptive control,[2–4] optimal control,[5,6] geometric approach,[7] Lyapunov control,[8–10] robust H_∞ control,[11–13] sliding mode control,[14–18] and finite time control.[19–21]

In practice, external disturbances always exist in space in the form of radiation torque, gravitational torque, and other environmental torques. The existence of external disturbances may destroy system performance, induce vibration, and result in instability. Many methods have been reported in the literature for inhibiting the influence of external disturbances, such as Refs. [6,11–14]. In Ref. [6], a robust and optimal attitude control law is presented for spacecraft with external disturbances. This control law is based on the min–max approach and the inverse optimal approach. On the basis of the H_∞ method, a local stabilization result is derived in Ref. [11], and a global stabilization control law is further designed in Ref. [12]. A controller scheme based on sliding mode control is employed in Ref. [14]. This scheme shows a good robustness to disturbances. However, chattering is an unavoidable problem while using sliding mode control.

Another effective feedback control technique against disturbances is the finite time control method.[21–23] Compared

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Peer review under responsibility of Editorial Committe of CJA.

Production and hosting by Elsevier

1000-9361
http://dx.doi.org/10.1016/j.cja.2013.04.032

with conventional asymptotically stable systems, finite time stable systems have two advantages: better disturbance rejection performance and faster convergence property around the equilibrium point.[24] In view of the superiorities, the finite time control technique has been used in various fields including robotic systems[25,26] and general system.[27,28] In addition, the finite time control method has also been employed to deal with the problem of attitude control of spacecraft. For example, based on the terminal sliding mode method and the finite time control technique, a discontinuous finite time controller is designed in Ref. [19]. In Ref. [20], the problem of global set stabilization is considered for a rigid spacecraft in the presence of external disturbances. Moreover, it is verified that the system states of the spacecraft with disturbances will be driven into a small neighborhood of a set consisting of two equilibria. In Ref. [21], on the basis of optimal control and finite-time control techniques, a pseudo-optimal control law is developed. The use of this control law can make the system trajectory converge to a neighborhood of the equilibrium set in the presence of disturbances.

As is well-known, in a spacecraft attitude control system, it is not easy to measure the disturbances. Under these circumstances, disturbance estimation has become a feasible method for measuring disturbances, for example, extended state observer[18,29] and disturbance observer (DOB). The DOB method is originally proposed in Ref. [30] and has been widely employed for feedforward compensation design. At present, DOB-based control (DOBC) techniques for linear and nonlinear systems have been developed and used in a lot of control fields, e.g., space manipulator,[31] robotic systems,[32] hard disk drive systems,[33,34] grinding systems,[35] and general systems.[36–38]

In this paper, a composite control strategy, combining the finite time control law in the feedback path with a feedforward compensation part on the basis of a linear DOB, is developed for the attitude control of a rigid spacecraft in terms of Rodrigues parameters. In relation to the existing literature, the main contributions of this work are as follows. By a coordinate transformation, the system can be regarded as three second-order subsystems, which is much clearer and easier for finite time controller design than the method in Ref. [19]. The DOB is used to estimate not only the external disturbances but also the coupling terms, which include the external disturbances and the system states. The proposed method combines two disturbance rejection control techniques, that is, the finite time control technique and the DOB technique; the combination of these two techniques has obvious advantages in terms of the convergence and disturbance rejection performance.

2. Preliminaries and model description

2.1. Preliminaries

Definition 1. [39]

(1) Given $[r_1 \quad r_2 \quad \cdots \quad r_n] \in \mathbf{R}^n, r_i > 0$, a continuous function $\mathcal{V}(\boldsymbol{x}) \in C(\mathbf{R}^n, \mathbf{R})$ is homogeneous of degree $\zeta > 0$ if there exists a positive real number $\zeta \in \mathbf{R}$ such that $\forall \boldsymbol{x} \in \mathbf{R}^n \setminus \{0\}, \varepsilon > 0, \mathcal{V}(\varepsilon^{r_1}x_1, \varepsilon^{r_2}x_2, \cdots, \varepsilon^{r_n}x_n) = \varepsilon^{\zeta}\mathcal{V}(x_1, x_2, \cdots, x_n)$.

(2) If there exists a real number $\zeta \in \mathbf{R}$ such that for $l = 1, 2, \ldots, n, \forall \boldsymbol{x} \in \mathbf{R}^n \setminus \{0\}, \varepsilon > 0, \hbar_l(\varepsilon^{r_1}x_1, \varepsilon^{r_2}x_2, \cdots, \varepsilon^{r_n}x_n) = \varepsilon^{\zeta + r_l}\hbar_l(\boldsymbol{x}), \quad [r_1 \quad r_2 \quad \cdots \quad r_n] \in \mathbf{R}^n, r_l > 0$, then a vector field $\hbar(\boldsymbol{x}) \in C(\mathbf{R}^n, \mathbf{R}^n)$ is called to be homogeneous of degree ζ.

(3) A homogeneous p-norm is presented as $\|\boldsymbol{x}\|_{\Delta,p} = \left(\sum_{l=1}^{n} |x_l|^{p/r_l}\right)^{1/p}, \forall \boldsymbol{x} \in \mathbf{R}^n$, for a constant $p \geqslant 1$. For simplicity, in this paper, $p = 2$ is chosen and the norm is written as $\|\boldsymbol{x}\|_{\Delta} = \|\boldsymbol{x}\|_{\Delta,,2}$.

Definition 2. [40]The system $\dot{\boldsymbol{y}} = \hbar_1(t, \boldsymbol{y}, \boldsymbol{u}_\alpha), \boldsymbol{y} \in \mathbf{R}^n, \quad \boldsymbol{u}_\alpha \in \mathbf{R}^m$ is said to be input state stability (ISS) if there exist a class $\mathcal{KL}$ function β and a class $\mathcal{K}$ function γ such that for any initial state $\boldsymbol{y}(t_0)$ and any bounded input $\boldsymbol{u}_\alpha(t)$, the solution $\boldsymbol{y}(t)$ exists for all $t \geqslant t_0$ and satisfies

$$\|\boldsymbol{y}(t)\| \leqslant \beta(\|\boldsymbol{y}(t_0)\|, t - t_0) + \gamma(\sup_{t_0 \leqslant \bar{\tau} \leqslant t} \|\boldsymbol{u}_\alpha(\bar{\tau})\|)$$

such a function γ is often referred to as an ISS-gain for the system.

Lemma 1. [24]*Consider the system* $\dot{y}_2 = \hbar_2(y_2), \hbar_2(0) = 0, y_2 \in \mathbf{R}$. *Suppose there exists a continuous function* $\mathcal{V}_2(y_2) : U \to \mathbf{R}$ *such that* $\mathcal{V}_2(y_2)$ *is positive definite and there exist real numbers* $c > 0$ *and* $\alpha \in (0, 1)$ *and an open neighborhood* $U_0 \subset U$ *of the origin satisfying* $\dot{\mathcal{V}}_2(y_2) + c\mathcal{V}_2^{\alpha}(y_2) \leqslant 0, y_2 \in U_0 \setminus \{0\}$. *Then, the origin is a finite-time stable equilibrium of the system. If* $U = U_0 = R$, *the origin is a globally finite time stable equilibrium of the system.*

Lemma 2. [19]*Consider the system* $\dot{x}_1 = 0.5x_2, \dot{x}_2 = \boldsymbol{u}_\beta$ *under the controller*

$$\boldsymbol{u}_\beta = -\frac{k_1}{2}(x_2^q + k_2^q x_1)^{2/q-1}$$

where $k_2 \geqslant 2^{1-1/q} + k_3, k_1 \geqslant k_2^{1+q}\left(2 - \frac{1}{q}\right)\left(2^{1-1/q} + \frac{2^{2-2/q}}{k_2} + k_3\right)$, $k_3 > 0, 1 < q = q_1/q_2 < 2, q_1$ *and* q_2 *are positive odd integers, then the closed-loop system is finite time stable.*

Lemma 3. [41]*Let* $\mathcal{V}(\boldsymbol{x}) : \mathbf{R}^n \to \mathbf{R}$ *be a homogenous function of degree* ζ *with respect to* $[r_1 \quad r_2 \quad \ldots \quad r_n]$. *Then the two conditions hold.*

(1) *The homogeneous degree of function* $\frac{\partial \mathcal{V}}{\partial x_i}$ *is* $\zeta - r_i$, *where* r_i *is the homogeneous weight of* x_i.

(2) *There is a constant* c *such that* $\mathcal{V}(\boldsymbol{x}) \leqslant c\|\boldsymbol{x}\|_{\Delta}^{\zeta}$. *Moreover,* $\underline{c}\|\boldsymbol{x}\|_{\Delta}^{\zeta} \leqslant \mathcal{V}(\boldsymbol{x})$, *where* $\underline{c}$ *is a positive constant, if* $\mathcal{V}(\boldsymbol{x})$ *is positive definite function.*

Lemma 4. [39]*Consider cascade system*

$$\dot{x}_1 = \hbar_1(t, x_1, x_2) \tag{1}$$

$$\dot{x}_2 = \hbar_2(t, x_2) \tag{2}$$

If the following conditions are hold