ARTICLE IN PRESS
JID:AESCTE AID:3277 /FLA [m5G; v1.149; Prn:17/03/2015; 14:25] P.1 (1-6)
Aerospace Science and Technology ••• (••••) •••–•••
Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

Robust attitude maneuver control of spacecraft with reaction wheel low-speed friction compensation

Shunan Wu [a,b,*], Rui Wang [a,b], Gianmarco Radice [c], Zhigang Wu [b]

[a] School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, PR China
[b] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, PR China
[c] Space Advanced Research Team, School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

A R T I C L E I N F O

Article history:
Received 20 December 2014
Accepted 9 March 2015
Available online xxxx

Keywords:
Attitude control
Robust control
Wheel friction
Observer
Spacecraft

A B S T R A C T

This paper investigates the attitude control problem in the presence of wheel low-speed friction and external disturbances. The critical issues surrounding wheel friction are firstly discussed, and the spacecraft attitude model and wheel friction model are introduced. A friction observer that can effectively estimate the friction torque is developed. An observer-based sliding mode controller, to perform attitude maneuver, is then proposed. By constructing a particular Lyapunov function, the stability and performance of the proposed controller for the closed-loop systems is discussed theoretically. Numerical simulations are finally provided, and the results have demonstrated that the friction is compensated by the observer and the proposed controller has better transient and steady-state performance.

1. Introduction

Attitude control is a key requirement for space missions, that rely on paradigms of spacecraft formation flying, stereoscopic mapping, imaging, telecommunications and other applications [1,2]. Many works on attitude control have been reported, and different approaches are proposed [3–6]. Due to their small weight, high reliability and agility, reaction wheels are commonly used actuators that store and exchange angular momentum to generate the necessary torques to perform attitude maneuvers. This is particularly true for some small spacecraft platforms, which require high precision pointing, accurate stabilization and rapid maneuver [7–10]. Periodic disturbances and perturbations could however lead to speed reversals, also known as zero-crossings, which may cause an abrupt increase in the spacecraft attitude maneuver errors. Besides, the wheel speed measurement is usually less precise near zero, which also increases the zero-crossing undesirable effect. More specifically, the reaction wheels have an inherent nonlinearity at zero-crossings of wheel speed due to the rolling motion of a bearing ball and its adjacent traces. If the angular speed of a reaction wheel is very low, the rolling motion enters into the friction region and static friction will dominate the relationship between commanded and actual control torques, while the friction torque will greatly decrease with the increasing of a reaction wheel speed, and degrades spacecraft attitude control. It is imperative therefore to compensate the static friction to achieve a high-accuracy attitude maneuver. Previous studies have proposed different approaches to address this problem [11–15]. The most commonly used methodology is to compensate the static friction by using high gain robust control. A variable–structure controller has been proposed to perform attitude maneuver in [11], where the static friction of reaction wheels is considered as the model uncertainty. A robust nonlinear control law, to improve attitude control performances in the presence of wheel friction, is developed in [12], and the results demonstrate that the proposed control law is convincing for zero-speed wheel. A set of proper speed controllers based on variable–structure control theory are designed to adjust the satellite to a desired attitude in the presence of unknown Coulomb friction and parametric uncertainties [13]. Another method attempts to eliminate static friction through a high gain wheel speed feedback. Specifically, a dither signal that harmonically linearizes the discontinuity of rolling solid friction has been implemented [14]. An attitude control system with reaction wheel friction compensation in which the actual wheel speed tends toward the ideal wheel speed by summing up the speed error with the torque command has been proposed in [15]. One promising methodology is to compensate the static friction by adding a command torque which approximates the static friction torque. The observer can therefore provide a possible solution to estimate the friction and be included in the control input.

To advance the research in the high-accuracy attitude maneuver control considering reaction wheels friction and external dis-

* Corresponding author at: School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, PR China. Tel./fax: +86 411 84706202.
E-mail address: wushunan@dlut.edu.cn (S. Wu).

http://dx.doi.org/10.1016/j.ast.2015.03.005
1270-9638/© 2015 Published by Elsevier Masson SAS.

Please cite this article in press as: S. Wu et al., Robust attitude maneuver control of spacecraft with reaction wheel low-speed friction compensation, Aerosp. Sci. Technol. (2015), http://dx.doi.org/10.1016/j.ast.2015.03.005

turbances, we make use of friction compensation observer and sliding mode control techniques. The kinematics and dynamics of a spacecraft with reaction wheels are firstly summarized, and the influence of the wheels' low-speed friction on the attitude maneuver is discussed. A friction observer to estimate the friction torque is then designed and an observer-based controller to perform attitude maneuver in the presence of disturbances and wheels' friction is proposed. The effectiveness of the proposed controller is finally demonstrated through numerical simulations.

2. Problem definition

2.1. Attitude kinematics and dynamics

The kinematic equation of a spacecraft in terms of the quaternion is given by [16]

$$\dot{Q} = \frac{1}{2}\left(q_0 I + Q^{\times}\right) \cdot \omega$$
$$\dot{q}_0 = -\frac{1}{2} Q^T \omega \tag{1}$$

where $Q = [q_1, q_2, q_3]^T$ and q_0 represent the vector component and the scalar component of a unit quaternion respectively. For any vector σ, $\sigma^{\times}$ denotes the cross matrix and is given by

$$\sigma^{\times} = \begin{bmatrix} 0 & -\sigma_3 & \sigma_2 \\ \sigma_3 & 0 & -\sigma_1 \\ -\sigma_2 & \sigma_1 & 0 \end{bmatrix} \tag{2}$$

The reaction wheels are orthogonally located along the body axes and the dynamics of a rigid spacecraft with wheels is governed by the following equation [17]

$$(J_S + J_W)\dot{\omega} + \omega \times \left[(J_S + J_W)\omega + J_W \Omega\right] = T_R + T_D \tag{3}$$

where J_S is the moment of inertia of spacecraft, J_W denotes the moment of inertia of wheels, ω represents the angular velocity of spacecraft, T_D represents the bounded disturbance torque, T_R denotes the actual torque, Ω is the wheel speed, and satisfies that $\dot{\Omega} = -J_W^{-1} T_R - \dot{\omega}$.

2.2. Reaction wheel friction model

A reaction wheel is not only driven by a motor's electromagnetic torque T_C, but also resisted by friction torque T_F, such that T_R is given by

$$T_R = T_C + T_F \tag{4}$$

The motor torque T_C, which is equivalent to the torque produced by the controller, is generally considered to approximate the torque T_R for simplification in design. However, this simplification will fail completely in the case of requiring smooth, bi-directional control with nominal zero speed reaction wheels.

Although we can qualitatively describe the characteristics of wheel friction, an accurate model is actually difficult to be obtained by computation but depends on experiments due to its complicated mechanism. Dahl has derived and experimentally verified a mathematical model for wheel friction, which is already used in the attitude control system of LandSate-D [18]. Stetson has further modified this model by taking account of viscous friction, and then the friction torque and angular speed of the wheels satisfy the following equations [11]

$$\begin{bmatrix} \dot{\Omega} \\ \dot{T}_F \end{bmatrix} = \begin{bmatrix} -J_W^{-1}(T_F + D\Omega + T_C) \\ \beta_0 \Omega (T_F \operatorname{sign}(\Omega) - T_{F0})^2 \end{bmatrix} \tag{5}$$

where D represents the viscous friction coefficient, β_0 is the rest slope parameter of the bearing, and T_{F0} denotes the Coulomb friction torque. Eq. (5) can rewritten as

$$\begin{bmatrix} \dot{\Omega} \\ \dot{T}_F \end{bmatrix} = \begin{bmatrix} -J_W^{-1} D & -J_W^{-1} \\ \beta_0 T_{F0}^2 & 0 \end{bmatrix} \begin{bmatrix} \Omega \\ T_F \end{bmatrix} + \Psi(x) \tag{6}$$

where $x = [\Omega \ \ T_F]^T$, and $\Psi(x)$ represents the high-order state of x since $\lim_{|x| \to 0} \frac{|\Psi(x)|}{|x|} = 0$. It should be noted that the satellite angular acceleration effect on the wheel speed derivative is ignored in Eq. (5) since it's much smaller than the other terms. The linear component of Eq. (6) guarantees the stabilization at the equilibrium of $\Omega = T_F = 0$, which will capture the wheel motion during zero-crossings. Namely, when the wheel speed crosses zero, the control input is very small such that the reaction wheels cannot get rid of the attraction of the equilibrium. Therefore, the actual control torques T_R will approach zero asymptotically and cannot drive the attitude maneuvers until the attitude errors become large enough. This phenomenon may severely disturb attitude control accuracy.

3. Controller design

To compensate the static friction and perform high-accuracy attitude maneuvers, a friction observer and an observer-based controller are proposed in this section. Due to the good transient performance and the ideal robustness to various disturbances, fast terminal sliding mode control appears to be a promising approach to tackle the problem under analysis [19]. The objective is to design a controller such that $(Q \to 0, \omega \to 0)$ can be achieved in the presence of disturbances and wheel friction.

3.1. Friction observer

The observer is used to estimate the friction torque and then compensate the static friction in the closed-loop system. We therefore propose the following friction observer according to Eq. (5)

$$\begin{bmatrix} \dot{\hat{\Omega}} \\ \dot{\hat{T}}_F \end{bmatrix} = \begin{bmatrix} -J_W^{-1}(\hat{T}_F + D\hat{\Omega} + T_C) + k_1(\Omega - \hat{\Omega}) \\ k_2(\Omega - \hat{\Omega}) \end{bmatrix} \tag{7}$$

where $\hat{\Theta}$ represents the estimated value for any variable Θ (such as Ω and T_F), k_1 and k_2 denote the observer gains, which will influence the performance of the friction observer. To discuss the convergence, the estimated error is firstly defined as follows

$$\tilde{x} = x - \hat{x} \tag{8}$$

where $\tilde{x} = [\tilde{\Omega} \ \ \tilde{T}_F]^T$ is the estimated error and $\hat{x} = [\hat{\Omega} \ \ \hat{T}_F]^T$. Substituting Eqs. (5) and (7) into Eq. (8) yields

$$\dot{\tilde{x}} = A_0 \tilde{x} + u \tag{9}$$

where

$$A_0 = \begin{bmatrix} -J_w^{-1} D - k_1 & -J^{-1} \\ -k_2 & 0 \end{bmatrix}, u = \begin{bmatrix} 0 \\ \beta_0 \Omega (T_F \operatorname{sign}(\Omega) - T_{F0})^2 \end{bmatrix}$$

which satisfies $\|u\| \le c$ and c denotes the upper bound. Solving Eq. (9) yields

$$\tilde{x}(t) = \tilde{x}(0) e^{A_0 t} + \int_0^t e^{A_0(t-\tau)} u(\tau) \mathrm{d}\tau \tag{10}$$