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Active vibration suppression for maneuvering spacecraft with high flexible appendages

Qiufan Yuan, Yanfang Liu *, Naiming Qi

School of Astronautics, Harbin Institute of Technology, Harbin, China

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ABSTRACT

The rotational and translational coupling effects that exist in the dynamics of the maneuvering spacecraft with high flexible structures are considered in this paper. The active vibration suppression using the modified positive position feedback control law is applied to the maneuvering spacecraft. The active vibration controller is designed based on the coupling dynamics. Using the calculated coupling parameters, the controller parameters are optimized via the M-norm optimization method. The controller is verified mathematically and experimentally. An air bearing spacecraft simulator is built to carry out the experiment. Simulation and experiment results show that the vibration of the flexible structures is efficiently suppressed by the designed controller and more residual vibration is reduced compared with the same controller without considering the coupling effects. The stability of the angular velocity is improved. As a conclusion, the proposed controller is efficient. The rotational and translational coupling effects should be considered in designing the vibration controller of maneuvering spacecraft.

1. Introduction

NEW aerospace missions put forward strong requirements on maneuverability of spacecraft. Spacecraft which can achieve fast capturing and precise pointing have caught increasing attention. However, the vibration of the flexible structures may reduce the pointing precision. To realize more efficient and precise maneuver, the vibration of the high flexible structure needs to be suppressed passively, semi-actively [1] or actively.

In recent years, active vibration control (AVC) of cantilever beams or plate structures has been studied. Controllers, such as rate feedback control [2], resonant control [3], positive position feedback (PPF) control [4], modified positive position feedback (MPPF) control [5], novel hybrid positive feedback control [6], etc., have been proposed. Linear quadratic regulator (LQR) controller [7], Wave-absorbing controller [8] and adaptive methods [9] are also proposed to suppress the vibration.

Moheimani [10] introduced a feed-through item into the transfer function from piezoelectric actuators to piezoelectric sensors to compensate for the modal truncated error. The parameters of the PPF controller are difficult to tune since the improvement of the PPF damping rate will cause the shift of the controlled frequency, which will reduce the effectiveness of the vibration suppression. To overcome this disadvantage, Mahmoodi proposed MPPF controller consisting of two compensators, namely the damping compensator and the stiffness compensator.

In most research papers, the integration of attitude control and smart structure vibration control was established to improve the spacecraft attitude control effectiveness. Hu et al. [11] designed an attitude variable structure controller based on the simplified attitude dynamic model of flexible spacecraft, which was proposed by Gennaro [12]. The PPF controller was optimized via LQR. Hu [13] also combined PD attitude controller with PPF vibration controller to suppress vibration of flexible spacecraft during attitude maneuvers. In the modeling of flexible spacecraft, the coupling dynamics and the orbit maneuver were not considered. Yuan et al. [14] combined the vibration suppression controller with the adaptive robust attitude controller to improve the precision of attitude control. Orszulik and Shan [15] combined the input shaping and multi-mode adaptive positive position feedback to realize vibration suppression on a flexible manipulator, the dynamics of which was similar to a maneuver spacecraft.

For the spacecraft with low flexible structures, the translational coupling effect is not obvious. When the flexibility of the structures is high enough, namely for the maneuvering spacecraft with small center rigid body and large flexible appends, both of the rotational and translational coupling effects should be considered [16]. These coupling effects are described as symmetric and anti-symmetric modes and demonstrated experimentally via a free floating platform [17–19]. With

* Corresponding author.
E-mail addresses: yuanqiufan@hotmail.com (Q. Yuan), liu-yanfang@hotmail.com (Y. Liu).

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the purpose of reducing on-off actuators' influence on the flexible dynamics, control modulation techniques like bang-bang (BB) technique, pulse width modulation (PWM), pulse width pulse frequency modulation (PWPM), and linear quadratic regulator (LQR) control law are detailed studied and tested [19,20].

In this paper, a different approach is proposed to improve the performance of attitude control. The vibration of the flexible appendages is controlled actively using piezoelectric sensors and actuators considering both of the rotational and translational coupling effects.

The remainder of the paper is organized as follows. In Section 2, a reduced dynamic model of spacecraft with two symmetric panels is constructed with the rotational and translational coupling effects taken into consideration. The coupling dynamic model parameters are calculated. In Section 3, the MPPF control law is adopted and controller parameters are optimized with an M-norm optimization method. In Section 4, simulations are carried out to explore the effect of the coupling dynamics on the controller design. In Section 5, an air bearing spacecraft simulator is constructed to verify the proposed control law experimentally.

2. Coupling dynamic model of maneuvering spacecraft

As shown in Fig. 1, the spacecraft consisting of a rigid body and two symmetric flexible beams is considered. It is assumed that the spacecraft maneuvers in the plane and the rotation angle is small. The coupling effect between the rigid body and the flexible structure is obvious when the spacecraft rotates about y-axis or moves along z-direction. While due to the small angle assumption, the coupling effect is not obvious and can be ignored when the spacecraft moves along the x-direction. Thus, a reduced dynamic model is constructed [21].

$$\begin{cases} m\ddot{z} + \mathbf{B}_{\mathrm{t,s}}\ddot{\eta}_s + \mathbf{B}_{\mathrm{t,n}}\ddot{\eta}_{\mathrm{n}} = u_{\mathrm{F}} \\ J\ddot{\theta} + \mathbf{B}_{\mathrm{r,s}}\ddot{\eta}_s + \mathbf{B}_{\mathrm{r,n}}\ddot{\eta}_{\mathrm{n}} = u_{\mathrm{M}} \\ \ddot{\eta}_s + 2\mathbf{H}\boldsymbol{\Omega}\dot{\eta}_s + \boldsymbol{\Omega}^2\eta_s + \mathbf{B}_{\mathrm{t,s}}^{\mathrm{T}}\ddot{z} + \mathbf{B}_{\mathrm{r,s}}^{\mathrm{T}}\ddot{\theta} = 0 \\ \ddot{\eta}_{\mathrm{n}} + 2\mathbf{H}\boldsymbol{\Omega}\dot{\eta}_{\mathrm{n}} + \boldsymbol{\Omega}^2\eta_{\mathrm{n}} + \mathbf{B}_{\mathrm{t,n}}^{\mathrm{T}}\ddot{z} + \mathbf{B}_{\mathrm{r,n}}^{\mathrm{T}}\ddot{\theta} = 0 \end{cases} \tag{1}$$

where m and J are the mass and the inertia around y-axis of the rigid body, z is the displacement along z-direction, θ is the rotation angle around y-axis, $\mathbf{B} \in \mathrm{R}^{1\times N_{\mathrm{m}}}$ is the coupling coefficients matrix, $\eta \in \mathrm{R}^{N_{\mathrm{m}}\times 1}$ is the vector of generalized coordinates of the flexible beams. Diagonal matrixes $\mathbf{H} = \mathrm{diag}(\xi_i)$ and $\boldsymbol{\Omega} = \mathrm{diag}(\omega_i)$ with ξ_i and ω_i being the i-th mode damping ratio and modal frequency of the panel under cantilever state, respectively. Subscripts (s) and (n) represent south beam and north beam, respectively. Subscripts (r) and (t) refer to rotation and translation, respectively.

The symmetry feature of the panels yields that

$$\begin{cases} \mathbf{B}_{\mathrm{r,s}} = \mathbf{B}_{\mathrm{r,n}} \\ \mathbf{B}_{\mathrm{t,s}} = -\mathbf{B}_{\mathrm{t,n}} \end{cases} \tag{2}$$

Substitution of Eq. (2) into the Eq. (1) results in

$$\begin{cases} m\ddot{z} + \mathbf{B}_{\mathrm{r}}\ddot{\eta}_{\mathrm{t}} = u_{\mathrm{F}} \\ J\ddot{\theta} + \mathbf{B}_{\mathrm{t}}\ddot{\eta}_{\mathrm{r}} = u_{\mathrm{M}} \\ \ddot{\eta}_{\mathrm{t}} + 2\mathbf{H}\boldsymbol{\Omega}\dot{\eta}_{\mathrm{t}} + \boldsymbol{\Omega}^2 + 2\mathbf{B}_{\mathrm{t}}^{T}\ddot{z} = 0 \\ \ddot{\eta}_{\mathrm{r}} + 2\mathbf{H}\boldsymbol{\Omega}\dot{\eta}_{\mathrm{r}} + \boldsymbol{\Omega}^2 + 2\mathbf{B}_{\mathrm{r}}^{T}\ddot{\theta} = 0 \end{cases} \tag{3}$$

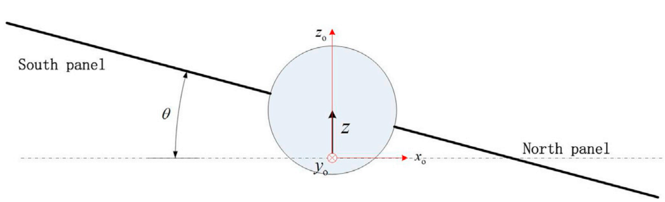

Fig. 1. A reduced model of maneuvering spacecraft.

where, $\eta_{\mathrm{t}} = \eta_{\mathrm{s}} + \eta_{\mathrm{n}}$, $\eta_{\mathrm{r}} = \eta_{\mathrm{n}} - \eta_{\mathrm{s}}$, $\mathbf{B}_{\mathrm{r}} = \mathbf{B}_{\mathrm{r,n}}$ and $\mathbf{B}_{\mathrm{t}} = \mathbf{B}_{\mathrm{t,n}}$. η_{t} and η_{r} denote the generalized coordinates of the translational and rotational coupling modes, respectively. Eq. (3) can be further expressed in the form

$$\begin{cases} \ddot{\eta}_{\mathrm{t}} + 2\mathbf{H}_{\mathrm{t}}\boldsymbol{\Omega}_{\mathrm{t}}\dot{\eta}_{\mathrm{t}} + \boldsymbol{\Omega}_{\mathrm{t}}^2\eta_{\mathrm{t}} = 0 \\ \ddot{\eta}_{\mathrm{r}} + 2\mathbf{H}_{\mathrm{r}}\boldsymbol{\Omega}_{\mathrm{r}}\dot{\eta}_{\mathrm{r}} + \boldsymbol{\Omega}_{\mathrm{r}}^2\eta_{\mathrm{r}} = 0 \end{cases} \tag{4}$$

where

$$\begin{cases} \mathbf{H}_{\mathrm{t}} = \mathbf{H}\mathbf{K}_{\mathrm{t}}^{-1} \\ \mathbf{H}_{\mathrm{r}} = \mathbf{H}\mathbf{K}_{\mathrm{r}}^{-1} \\ \boldsymbol{\Omega}_{\mathrm{t}} = \boldsymbol{\Omega}\mathbf{K}_{\mathrm{t}}^{-1} \\ \boldsymbol{\Omega}_{\mathrm{r}} = \boldsymbol{\Omega}\mathbf{K}_{\mathrm{r}}^{-1} \end{cases} \tag{5}$$

and

$$\begin{cases} \mathbf{K}_{\mathrm{t}} = \mathrm{diag}\left(\sqrt{1-\dfrac{2B_{\mathrm{t1}}^2}{m}}, \ldots, \sqrt{1-\dfrac{2B_{\mathrm{t}i}^2}{m}}, \ldots, \sqrt{1-\dfrac{2B_{\mathrm{t}N_m}^2}{m}}\right) \\ \mathbf{K}_{\mathrm{r}} = \mathrm{diag}\left(\sqrt{1-\dfrac{2B_{\mathrm{r1}}^2}{J}}, \ldots, \sqrt{1-\dfrac{2B_{\mathrm{r}i}^2}{J}}, \ldots, \sqrt{1-\dfrac{2B_{\mathrm{r}N_m}^2}{J}}\right) \end{cases} \tag{6}$$

, the parameters $B_{\mathrm{t}i}$ and $B_{\mathrm{r}i}$ are the i-th element of $\mathbf{B}_{\mathrm{t}}$ and $\mathbf{B}_{\mathrm{r}}$, respectively.

For the i-th mode, $\omega_{\mathrm{t}i}$ and $\omega_{\mathrm{r}i}$ are the translational coupling frequency and the rotational coupling frequency, respectively, and ξ_{ti} and ξ_{ri} are the translational and rotational coupling damping ratio, respectively. The rotational and translational coupling mode form a pair. Their frequencies are slightly larger than the natural frequency of the panel under cantilever state [18].

3. Vibration controller design

3.1. Composition of the vibration control system

As shown in Fig. 2, the control system consists of piezoelectric actuators and sensors, an amplifying circuit, a drive circuit and a control computer. Piezoelectric actuators and sensors are collocated bonded on the panel surface. The i-th sensor and i-th actuator are denoted by S_i and A_i, respectively. The coordinates of their two ends are denoted by x_{i1} and x_{i2} . The coordinates x_0 and x_l are the installation coordinate and the end coordinate of the panel, respectively.

3.2. Vibration controller design

For vibration control of the i-th mode, the basic form of MPPF is given as

$$\begin{cases} \ddot{\eta}_i + 2\xi_i\omega_i\dot{\eta}_i + \omega_i^2\eta = \omega_i^2(\alpha\gamma + \beta\lambda) \\ \ddot{\kappa} + 2\xi_{\mathrm{c}}\omega_{\mathrm{c}}\dot{\kappa} + \omega_{\mathrm{c}}^2\kappa = \omega_{\mathrm{c}}^2\eta \\ \dot{\lambda} + \omega_{\mathrm{d}}\lambda = \omega_{\mathrm{d}}\eta \end{cases} \tag{7}$$

where α and β are the stiffness gain and damping gain, respectively.

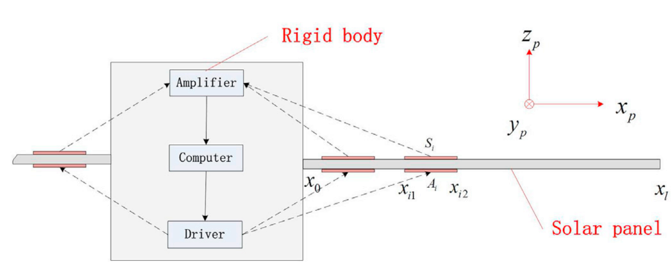

Fig. 2. Composition of the control system.