Spacecraft vibration reduction using pulse modulated command input and smart materials

Qinglei Hu
Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, People's Republic of China

Abstract
Purpose – To provide an approach to active vibration reduction of flexible spacecraft actuated by on-off thrusters during attitude control for spacecraft designers, which can help them analysis and design the attitude control system.
Design/methodology/approach – The new approach includes attitude controller acting on the rigid hub, designed by using pulse-width pulse-frequency modulation integrated with component command technique, and the piezoelectric material elements as sensors/actuators bonded on the surface of the beam appendages for active vibration suppression of flexible appendages, designed by optimal positive position feedback (OPPF) control technique. The OPPF compensator is devised by setting up a cost function to be minimized by feedback gains, which are subject to the stability criterion at the same time, and an extension to the conventional positive position feedback control design approach is investigated.
Findings – Numerical simulations for the flexible spacecraft show that the precise attitude control and vibration suppression can be accomplished using the derived vibration attenuator and attitude control controller.
Research limitations/implications – Studies on how to control the on-off actuated system under impulse disturbances are left for future work.
Practical implications – An effective method is proposed for the spacecraft engineers planning to design attitude control system for actively suppressing the vibration and at the same time quickly and precisely responding to the attitude control command.
Originality/value – The advantage in this scheme is that the controllers are designed separately, allowing the two objectives to be satisfied independently of one another. It fulfils a useful source of theoretical analysis for the attitude control system design and offers practical help for the spacecraft designers.

Keywords Spacecraft, Vibration

Paper type Technical paper

1. Introduction

The current trend of spacecraft is to use large, complex, and light weight space structures to achieve increased functionality at a reduced launch cost. The combination of large and light weight design results in these space structures being extremely flexible and having low fundamental vibration modes. These modes are often excited during normal on-orbit operations, such as attitude maneuvers, and so on, especially, when the spacecraft attitude control system employs on-off thrusters that produce discontinuous and nonlinear control actions. Therefore, designing an on-off thruster system to provide fine pointing accuracy while effectively suppressing the induced vibration poses a challenging task for spacecraft designers.

Research toward thruster control has been focused on mainly two areas: bang-bang control and pulse modulation (Anthony *et al.*, 1990; Hari, 1994; Wie and Plescia, 1984; Vander Velde and He, 1983). Bang-bang control is simple in formulation, but often results in excessive thruster action interacting with the flexible mode of the spacecraft, and limit cycles. On the other hand, pulse modulation, especially, the pulse-width pulse-frequency (PWPF) modulation is commonly employed due to their advantages of reduced propellant consumption, near-linear duty cycles and close to linear operation. On-off thruster firing, no matter the method of modulation, will introduce vibrations to the flexible structures to some degree. Effective methods to actively suppress the induced vibration are necessary and significant to fulfill mission requirements such as high-precision pointing, shape control and integrity of structures. Research in this area has been taken along two directions: one direction concentrates on modifying the input command to reduce vibrations and the other focuses on the active suppression of the induced vibrations.

A set of command-shaping techniques exists. These techniques work by altering the shape of either the actuator commands or the reference outputs, to reduce the oscillation of the system response. Input shaping (Singer and Seering, 1990; Sighose *et al.*, 1990) and component synthesis vibration suppression (CSVS) method (Shan, 2002; Jun *et al.*, 2004) are two commonly used methods to modify the input command in order to reduce vibrations of flexible structures. These two methods share the similar principle to reduce the vibration of the flexible structures, whereas the major difference between input shaping and CSVS lies in the design methodology of input command. Input shaping employs numerical input shaper before convolution. In contrast, by the CSVS method, the commands are directly designed without solving nonlinear equations and the CSVS commands can be of many forms. It is obvious that the CSVS method is simple and more intuitive than input shaping. CSVS method for systems with linear actuators has been successfully developed to act on modal vibrations as they occur. Recently, this method has been extended to systems with on-off actuators to some degree (Shan, 2002; Jun *et al.*,

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1748-8842.htm

Aircraft Engineering and Aerospace Technology: An International Journal
78/5 (2006) 378–386

[DOI 10.1108/00022660610685530]

Aircraft Engineering and Aerospace Technology: An International Journal
Volume 78 · Number 5 · 2006 · 378–386

2004). However, existing approaches require complicated nonlinear optimizations and result in bang-bang control action. The principal drawbacks term from an extensive set of optimization constraints which, in the presence of multiple. Closely spaced modes are extremely sensitive to initial state, number of modes, mode ratio, and move distance. Clearly, an approach which capitalizes on the strengths of CSVS method command without carrying the drawbacks is preferable.

In the area active vibration suppression, one promising method for actively suppressing the induced vibrations is to use piezoelectric materials as actuators/sensors since piezoelectric materials have the advantages of high stiffness, light weight, lower consumption, and easy implementation. With respect to the control of these smart structures, a wide range of approaches has been proposed. Positive position feedback (PPF) has been applied by feeding the structural position co-ordinate directly to the compensator and the product of the compensator and a scalar gain positively back to the structure in Song and Agrawal (2001), Fanson and Caughey (1990), Song *et al.* (1999) and Hu and Ma (2005a, b, c, 2006). Analytical and experimental studies also demonstrate that PPF offers quick damping for a particular mode provided that the modal characteristics are well known, and is easy to implement and possesses robustness to vibrations in modal frequency in Fanson and Caughey (1990). However, a difficult question on the PPF compensator design is to select a stabilizing set of feedback gains under the influence of multi-modes of vibration. The routine application of root *locus* analysis has limitations, especially for high-order multi-input systems; the spectral distribution of the system natural frequencies influences the closed-loop system performance in an undesirable manner; this is true in conjunction with arbitrary selected feedback gains. Although the selection of PPF gains is dictated by a stability criterion which is in the form of positive definiteness of a matrix consists of feedback gains and system parameters (Fanson and Caughey, 1990), it is not a straightforward procedure to rely on such a single criterion to find a desirable set of feedback gains. The stability criterion is a rather passive approach in the sense that one can have only stable region of feedback gains; no particular insight on the efficiency of the feedback gains is provided by the stability criterion alone. Therefore, especially for the multi-mode case, a more systematic approach is required for better performance of the compensator.

The goals of this paper are to propose a new approach to vibration reduction of flexible spacecraft actuated by on-off thrusters, by using PWPF modulated input component command based on CSVS method for attitude control and smart materials for active vibration suppression during the attitude maneuvers. The flexible model to be investigated is a hub with a cantilever flexible beam appendage, which can undergo a single-axis rotation. In this new approach, the CSVS method is used to modify the existing command so that less vibration will be caused by the command itself. Considering the on-off thruster actions, a scheme integrating CSVS method with a PWPF modulation is given. The unshaped PWPF modulated thruster control has been shown to excited fewer modal vibrations than bang-bang controller and the PWPF modulator itself has two primary advantages: its pseudo-linear operation and its capacity for real-time parameter tuning. On the contrary, the technique of optimal PPF (OPPF) control by setting up a cost function to be minimized by feedback gains, which are subject to the stability criterion at the same time, is used *e* for suppression of micro-vibrations, i.e. fine tuning the system at the final stage of operations, which is desirable for precision pointing of advanced spacecraft. Numerical simulations performed on a five-mode model of the spacecraft with flexible appendages during rest-to-rest maneuver demonstrate the effect and feasibility of the method. The rest of the paper is as follows: Section 2 presents the model of the spacecraft with flexible appendages-bonded piezoelectric material on its surface. Section 3 discusses the basics about the PWPF modulator. Section 4 gives the principle of the CSVS method. Section 5 introduces the smart structures used in this paper and the PPF control. Section 6 presents and analyzes the simulation results. Section 7 concludes the paper.

2. Dynamic modeling of a slewing active structure

Figure 1 shows the model of a flexible spacecraft, which consists of a rigid hub with radius b, a uniform cantilever flexible beam with surface-bonded piezoelectric sensors and actuators, the length l and the tip mass m_t. Define the OXY and oxy as the inertial frame and the frame fixed on hub, respectively. The attitude angle θ denotes the relative motion of these frames. Denotes $W(x,t)$ as the flexible deformation at x with respective to the oxy frame, where $x \in [0, l]$.

For system modeling, several assumptions are made:

- the beam is considered to be an Euler-Bernoulli beam and the axial deformation is neglected;
- the piezoelectric layer is homogeneous and is uniaxially polarized;
- the piezoelectric material is perfectly bonded to the beam; and
- the gravitational effect, hub dynamics and internal/external disturbances are neglected for simplicity.

The equations of motion for the flexible spacecraft with thrusters and smart materials sensors/actuators are (Hu and Ma, 2005a, b):

$$\mathcal{J}\ddot{\theta} + \sum_{i=1}^{n} D_i \ddot{q}_i = T \tag{1}$$

$$\ddot{q}_i + D\ddot{\theta} + Z\dot{q}_i + \lambda q_i = -Be_a \tag{2}$$

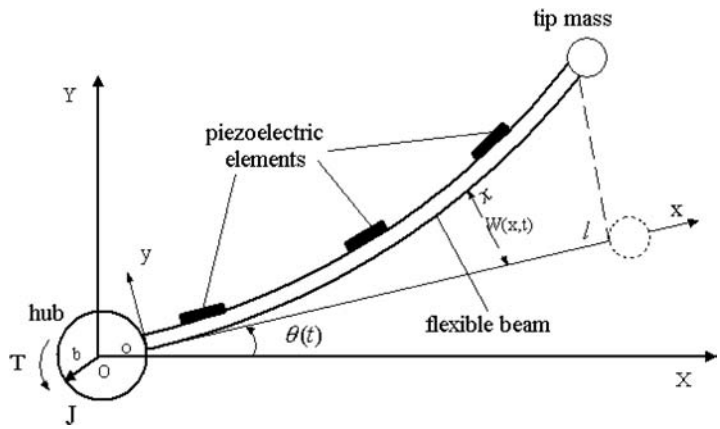
$$\gamma e = B^T q \tag{3}$$

where $\mathcal{J}$ is the flexible spacecraft moment of inertia, q_i is the modal co-ordinate, q is the modal co-ordinate vector, D_i is the rigid elastic coupling for each vibration mode, D is the rigid elastic coupling vector, Z is the modal damping matrix, λ is the matrix of natural frequencies, B^T is the electro-mechanical coupling term, γ is the constant of the piezoelectric material, and e is the electrical voltage.

3. PWPF modulator

The PWPF modulator has been used in the control systems of such spacecraft as the Agena satellite, INTELSAT-5, INSAT and ARABSAT. It produces a pulse command sequence to the thruster by adjusting the PWPF. In its linear range, the average torque produced equals the demand torque input. Compared with other methods modulation, the PWPF

Figure 1



modulator has several superior advantages such as closed-to-linear operation, high accuracy, and adjustable PWPF, which provide scope for advanced control.

This device, as shown in Figure 2, is composed of a Schmidt Trigger, a pre-filter, and a feedback loop. The Schmidt Trigger is simply an on-off relay with a dead-zone and hysteresis. When a positive input to the Schmidt Trigger is greater than U_{on}, the trigger output is U_m. Consequently, when the input falls below U_{off} the trigger output is 0. This response is also reflected for negative inputs. The errors signal $e(t)$ is the difference between the Schmidt Trigger output U_m and the system input $r(t)$. The error is fed into the pre-filter whose output $f(t)$ feeds the Schmidt Trigger.

The design parameters to be studied are the pre-filter coefficients k_m and τ_m, and the Schmidt Trigger parameters U_{on}, U_{off} and U_m. Selection of PWPF modulator parameters is an important issue. Improper setting of the parameters values will result in large output phase lag, excessive number of thruster firings and fuel consumption and even instability of the system. The PWPF modulation were usually fast compared to the spacecraft rigid body dynamics, and the static characteristics of the modulator were good enough for rigid spacecraft attitude controls. But the dynamics characteristics need to be investigated for the flexible spacecraft attitude control, and the analytic methods can be used to analyze them. However, due to the strongly nonlinear nature of the modulator, analytic methods such as describing function cannot produce accurately prediction over a large operation range. Instead, extensively numerical simulations can be carried out to study the effects of these parameters on the performance of the modulator. Two types of analysis: static analysis, and dynamic analysis are conducted to study different performance indices of the modulator and the rigid flexible system. The important performance indices of the modulator include modulation factor, thruster cycles (number of thruster firings), a total thruster on-time (fuel consumption). The important performance indices of the flexible spacecraft include steady error of the rigid body (indication of the stability), setting time of the rigid body, and modal response of the flexible appendage. This paper only presents results from the numerical studies and details on PWPF parameter selection can be found in Song and Agrawal (2001) and Song *et al.* (1999). The preferred range of parameters through extensive simulations is listed in Table I.

4. Component synthesis vibration suppression (CSVS) method

4.1 Principle of CSVS

The CSVS method possesses the feature that it can realize the specified rigid body motion of system while suppressing assigned vibration modes. In this section, the principle of the CSVS method is discussed briefly and the essence of CSVS method can be found in Shan (2002) and Jun *et al.* (2004) in details.

Considering the following equation (4), which is a generalized vibration system:

$$\ddot{x} + 2\varsigma\omega\dot{x} + \omega^2 x = F(t) \qquad (4)$$

where x is the state co-ordinate, ω is the natural frequency, ς is the damping ratio, and $F(t)$ is the control input. Note that the damped vibration frequency can be represented by $\omega_d = \omega\sqrt{1-\varsigma^2}$, and the corresponding period is $T_d = 2\pi/\omega_d$. Figure 3 demonstrates the simplest example of application of CSVS method. The vibration excited by impulse 1 at time 0, with the amplitude A, is cancelled by impulse 2 implemented at time $T_d/2$ with the amplitude

Figure 2

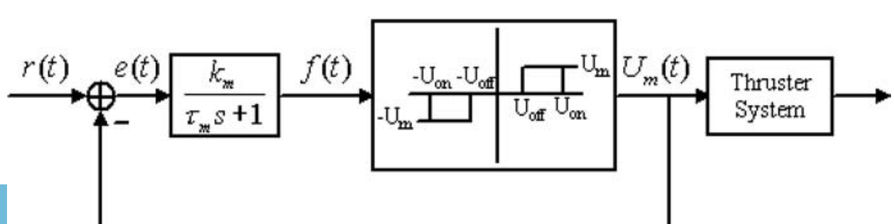


Table I Recommended range of PWPF parameters

	Static analysis	Dynamics analysis	Recommended settings
k_m	$2 < k_m < 6$	N/A	$2 < k_m < 6$
τ_m	N/A	$0.1 < \tau_m < 0.5$	$0.1 < \tau_m < 0.5$
U_{on}	$U_{on} > 0.3$	N/A	$U_{on} > 0.3$
U_{off}	$U_{on} < 0.8U_{on}$	N/A	$U_{off} < 0.8U_{off}$
U_m	N/A	1.0	1.0

$Ae^{-\pi\varsigma\sqrt{1-\varsigma^2}}$. Ideally, no vibration exists after such superimposition.

Remark 1. Figure 3 shows the simplest case, in which only two impulses exist. The CSVS method is a vibration self-cancelled method by which the vibration excited by the former input can be cancelled by the other inputs with suitable time delays.

The following lemma 1 gives the principle of CSVS method to design the component sequences:

Lemma 1. Given a vibration mode with the natural frequency ω, period T_d and damping ratio ς. Implementation of n similar components, whose amplitudes are scaled by an attenuation factor of $e^{-\varsigma\omega t}$ at n time instants of $0, T_d/n, \ldots, (n-1)T_d/n$ leads to suppression of this vibration mode completely.

Remark 2. The number of the input components, n, can be any positive integer, and the components can be in the form of either impulses or time variable functions. To realize the CSVS method, only the vibration frequencies and damping ratios must be known.

4.2 Robust CSVS method

According to lemma 1, just two parameters, vibration frequency and damping ratio, are used to construct the CSVS command. Ideally, all vibrations can be canceled after applying the CSVS commands, provided that these two parameters can be known exactly. In practice, however, due to estimation errors of these two parameters, vibration may still exit after applying the CSVS commands. A robust CSVS method is proposed and fully analyzed in Shan (2002) and Jun *et al.* (2004). The robustness can be recognized by the derivative of the system response with respect to the parameter.

To give the robust CSVS command, first, let us define the concept of order of robustness, which is defined as follows:

Definition. Given that the response of system (4) caused by an input command is $X(t)$, and the end time instant of the input command is t_f, if:

$$X(t > t_f) = 0, \left.\frac{\partial X(t > t_f)}{\partial \omega}\right|_{\omega_m} = 0, \left.\frac{\partial^2 X(t > t_f)}{\partial \omega^2}\right|_{\omega_m} = 0, \ldots, \left.\frac{\partial^n X(t > t_f)}{\partial \omega^n}\right|_{\omega_m} = 0$$

$$\text{and} \quad \left.\frac{\partial^{n+1} X(t > t_f)}{\partial \omega^{n+1}}\right|_{\omega_m} \neq 0,$$

then the input command is stable to suppress the vibration and with the nth-order robustness to be frequency error, where ω_m is the modeling (or estimated) frequency.

Now we show how to construct a robust CSVS command.

Lemma 2. If a CSVS input command can suppress a vibration mode with the pth-order robustness to the frequency estimation error, then the new command, formed by synthesizing n of such commands according to lemma1, can suppress the same vibration mode, but with the p + first-order robustness to the frequency error.

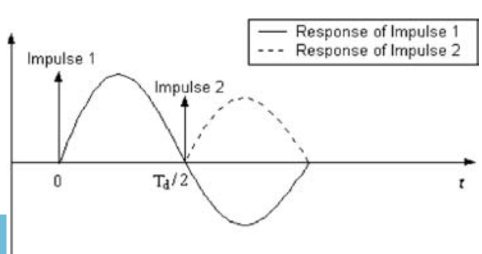
The CSVS method can also work on suppression of multiple modes of vibrations. The principle of constructing the multi-mode CSVS commands is similar to that of constructing the robust CSVS commands. The following lemma 3 gives the principle of constructing the multi-mode CSVS commands:

Lemma 3. If a CSVS input command can suppress $n-1$ vibration modes, then the new command, formed by synthesizing n of such commands according to lemma 1 to suppress the nth vibration mode, can suppress all the n vibration modes.

According to lemmas 1-3, various CSVS commands can be constructed, with any number of components n, any order of robustness and any multiple modes.

Remark 3. It should be pointed out that the number of components n plays an important role in CSVS commands. If n is too large, considerable online computational work will be needed, although the higher order robustness can be enhanced. If n is too small, the robustness for higher order modes will be degraded.

Figure 3 Basic principle of CSVS method



5. Smart structures and PPF control

A smart structure employs distributed sensors and actuators to apply localized strains to insure the system respond in a desired fashion. The smart structure has the capability to respond to a changing external environment (such as loads or shape change) as well as to a changing internal environment (such s damage or failure). Smart actuators can be used to alter system characteristics (such as stiffness or damping) as well as of system response (such as strain or shape) in a controlled manner. There are several types of embedded sensors candidates and actuators that can be used for vibration suppression and structural control, such as piezoelectric deformation sensors, fiber optic sensors, piezoelectric wafers, shape memory metal wires, piezoelectric polymer film, and so on. In this paper, piezoelectric material will be used as a sensor to detect and as an actuator to suppress structural vibration. Piezoelectric materials possess the property of piezoelectricity,

Aircraft Engineering and Aerospace Technology: An International Journal
Volume 78 · Number 5 · 2006 · 378–386

which describes the phenomenon of generating an electric charge in a material when subjected to a mechanical stress (direct effect), and conversely generating mechanical strain in response to an applied electric field. This property prepares piezceramic materials to function as both sensors and actuators and makes them attractive for structural control applications.

For control the flexible structures, the PPF control schemes is well suited for implementation utilizing the piezoelectric sensors and actuators. This approach has several desirable characteristics: it is insensitive to spillover, the method cannot be destabilized by finite actuator dynamics, and it is amenable to strain sensing since it uses generalized displacements.

The equations describing PPF control operation are given as (Fanson and Caughey, 1990):

$$\ddot{\eta} + D\dot{\eta} + \Omega\eta = a_1 C^T G\xi \qquad (5)$$

$$\ddot{\xi} + D_f\dot{\xi} + \Omega_f\xi = a_2\Omega_f C\eta \qquad (6)$$

where η is the modal co-ordinate vector describing displacement of the structure, D is the modal damping matrix of the structure, Ω is the modal frequency matrix of the structure, a_1 is a constant related to actuator sensitivity, G is the feedback gain matrix, ξ is the compensator co-ordinate vector, D_f the compensator damping matrix, $\Omega_f$is the compensator frequency matrix, a_2 is constant representing sensor sensitivity, and C is a fully populated participation matrix which determines the influence of each sensor/actuator pair on each compensator and vice versa.

The selection of PPF gains is dictated by a stability criterion, which is in the form of positive definiteness of a matrix consisting of feedback gains and system parameters as following:

Lemma 4. The stability condition for the two combined systems can be written as:

$$\Omega - a_1 a_2 C^T GC > 0 \qquad (7)$$

that is, the matrix should be positive define. Note that feedback gain matrix G consists of each feedback gain which is associated with each flexible mode.

For a single mode control with single compensator, the operation of the compensator can be illustrated by frequency domain analysis. The combined systems frequency response characteristics are shown in Figure 4. It is seen in the figure, when the PPF compensator's natural frequency is in the region of the structure's natural frequency, the structure experiences active damping. Additionally, when the compensator's natural frequency is lower than the structure's natural frequency, active flexibility results and when the compensator's natural frequency is larger than the structure's natural frequency, active stiffness results. Clearly, the controller efficiency is maximized when the compensator and system natural frequencies match together.

On the other hand, the effect of the compensator's damping ratio, ς_c, is also discussed as follows. Larger values of the damping ratio ς_c will result in a less steep slop thereby increasing the region of active damping. The difference in the slop of the phase angle can be shown from Figures 5 and 6 with $\varsigma_c = 0.1$ and $\varsigma_c = 0.5$. In this sense, a larger value of ξ_c ensures a larger region of active damping and therefore will increasing the robustness of the compensator with respect to uncertain modal frequency. However, it is expected to result in slightly less effective damping and in increased flexibility at lower modes as a trade-off.

Figure 4 Frequency response of system to PPF compensator

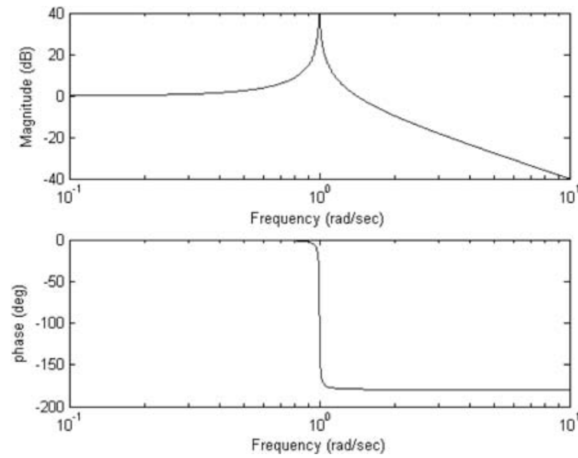


Figure 5 Bode plot with $\varsigma_c = 0.1$

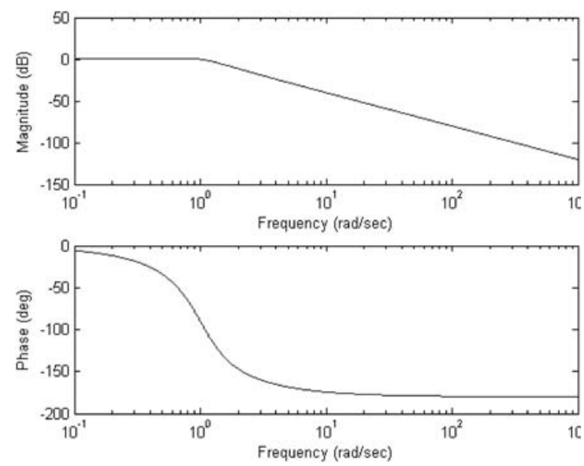
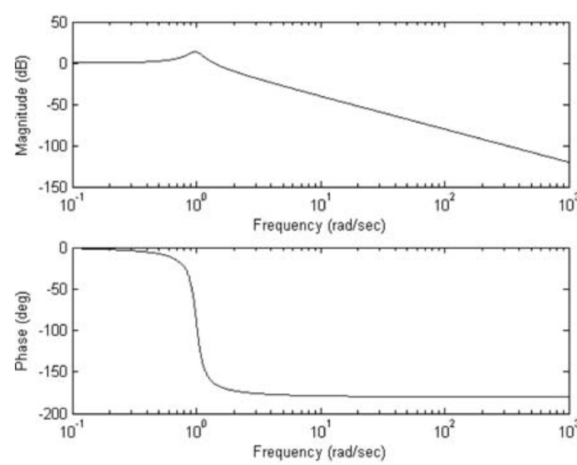


Figure 6 Bode plot with $\varsigma_c = 0.5$



Although the design of PPF compensator in the single mode case is quite straightforward, by direct selection of feedback gain, the design methodologies for multi-mode are not well developed. In order to select the feedback gain in a more systematical way, an optimal PPF control algorithm is given in the following.

Equations (5) and (6) can be rewritten in a first-order state space form:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\eta\\ \dot{\eta}\\ \xi\\ \dot{\xi}\end{bmatrix}=\begin{bmatrix}0 & I & 0 & 0\\ -\Omega & -D & a_1C^TG & 0\\ 0 & 0 & 0 & I\\ a_2\Omega_fC & 0 & -\Omega_f & -D_f\end{bmatrix}\begin{bmatrix}\eta\\ \dot{\eta}\\ \xi\\ \dot{\xi}\end{bmatrix} \tag{8}$$

The above equation, for notational simplicity, is written as:

$$\dot{x}=\bar{A}x \tag{9}$$

where $x=[\eta,\dot{\eta},\xi,\dot{\xi}]^{\mathrm{T}}$ is a state vector:

$$\bar{A}=\begin{bmatrix}0 & I & 0 & 0\\ -\Omega & -D & a_1C^TG & 0\\ 0 & 0 & 0 & I\\ a_2\Omega_fC & 0 & -\Omega_f & -D_f\end{bmatrix}$$

The cost function is to be minimized by the feedback gains subject to the constraint equation (7):

$$\mathcal{J}=\frac{1}{2}\int_0^\infty\left(x^TQ_sx+v_a^TQ_vv_a\right)\mathrm{d}t \tag{10}$$

Using equation (9), the cost function designed in equation (10) becomes:

$$\mathcal{J}=\frac{1}{2}x(0)^T[P_s+P_u]x(0) \tag{11}$$

where

$$P_s=\int_0^\infty e^{\bar{A}^Tt}Q_se^{\bar{A}t}\mathrm{d}t,\quad P_u=\int_0^\infty e^{\bar{A}^Tt}G^TQ_uGe^{\bar{A}t}\mathrm{d}t$$

or

$$\mathcal{J}(p)=\frac{1}{2}\mathrm{trace}[P_sX(0)+P_uX(0)],\quad X(0)=x(0)x(0)^{\mathrm{T}} \tag{12}$$

Hence, the optimization problem can be restated as follows:

$$\text{Minimize } \mathcal{J}=\frac{1}{2}\mathrm{trace}[\bar{P}X(0)] \tag{13}$$

subject to $\Omega-a_1a_2C^TGC>0$, where $\bar{P}=P_s+P_u$.

Note that P_s and P_u are positive definite matrices if $\bar{A}$is stable and satisfy the following Lyapunov equations:

$$P_s\bar{A}+\bar{A}^TP_s+Q_s=0\quad P_u\bar{A}+\bar{A}^TP_u+\bar{G}^TQ_u\bar{G}=0 \tag{14}$$

For this constraint optimization problem, it can easily be resolved using the MATLAB/optimization toolbox.

6. Simulation results and comparisons

To demonstrate the effectiveness of the proposed control schemes, numerical simulations have been performed and presented in this section. The parameters of the flexible spacecraft used in the simulation are from Hu and Ma (2005a, b). Because low-frequency modes are generally dominant in a flexible system, in this paper, the first two of five modes frequency 3.161 and 16.954 rad/s, respectively, are major concerns for vibration suppression. The type of PZT-5A piezoelectric ceramic plates is bonded to the surface of the flexible appendages. The material properties of the piezoceramics can be found in Song and Agrawal (2001).

In the simulation, the proportional gain and the derivative gain of the PD controller for attitude control are 15 and 50, respectively. For the PWPF modulator parameters, $k_m=3$, $\tau_m=0.15$, $U_{\mathrm{on}}=0.4$, $U_{\mathrm{off}}=0.15$, and $U_m=1$ are used in accordance with the recommendations from Table I and extensive numerical simulations trials. The OPPF compensator parameters $g_1=0.5$, $g_2=0.7$, $\omega_{c1}=2.55$, $\omega_{c2}=16.025$, $\zeta_{c1}=0.5$ and $\zeta_{c2}=0.5$ can be got by solving equation (13) subject to $\Omega-a_1a_2C^TGC>0$ using the MATLAB/optimization toolbox. It can be easy verified that the stability condition for the OPPF compensator is satisfied for both modes 1 and 2. For actively suppressing the relatively large amplitude vibrations, second-order robust with four components for the first mode, and second-order robust with four components for the first mode and zero-order robust with two components for the second mode for the multi-mode flexible system are employed.

For comparative purposes, two sets of simulation were conducted. The first set of simulations was conducted to demonstrate the effectiveness of the CSVS method and no the technique of active vibration suppression using smart material is used in this case. The flexible spacecraft was instructed to slew under an unshaped 60° step command. Two cases, with and without CSVS method, were performed in this set of simulation. In the case of PWPF modulated with CSVS method, the angular displacement and velocity of the rigid body converge to around its desired position, 60° and desired rate 0°/s, in about 18 s, respectively, as shown in Figure 7. At the steady state, about 0.1 and 0.02°/s period errors for the angle and angular velocity, respectively, in orientation are observed. The vibration energy level $E=\dot{q}^T\dot{q}+q^T\lambda q$ plot (vibration curves of the modes not shown because of space limitation) of the flexible appendages is reflected in the bottom of Figure 7. The vibration energy level almost dies out in 15 s with the maximum amplitude about 0.35 Nm.

On the other hand, when just PD control is used in the attitude subsystem, more severe rigid body and flexible appendages interaction is observed. The angular displacement and velocity of the rigid body converge to around its desired position, 60° and desired rate 0°/s, in about 20 s, respectively, as shown in Figure 8. But at steady state, about 0.25°and 0.1°/s period errors for the angle and angular velocity, respectively, in orientation are observed, which cannot be satisfied for the high-precision pointing requirements of the spacecraft. The vibration energy of the flexible appendages is reflected in Figure 8. The vibration energy level almost dies out in 20 s with the maximum amplitude of the vibration energy about 1.05 Nm. This first set of simulation demonstrates the effectiveness of the CSVS method for the vibration

Aircraft Engineering and Aerospace Technology: An International Journal
Volume 78 · Number 5 · 2006 · 378–386

Figure 7 Slew using PD with CSVS method

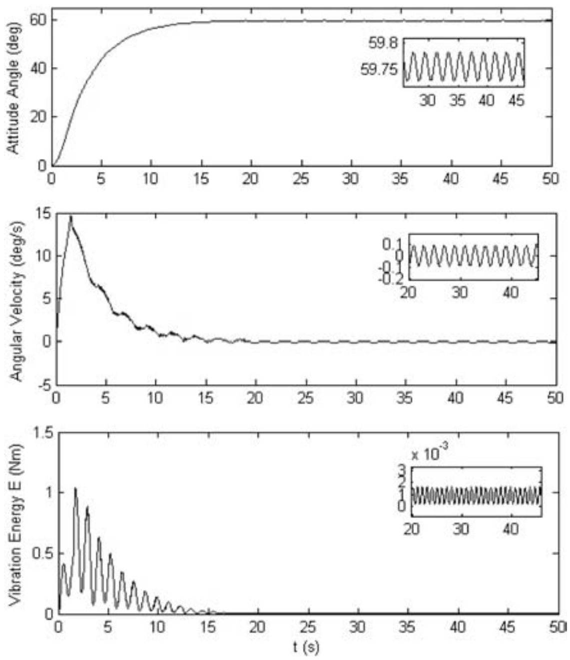
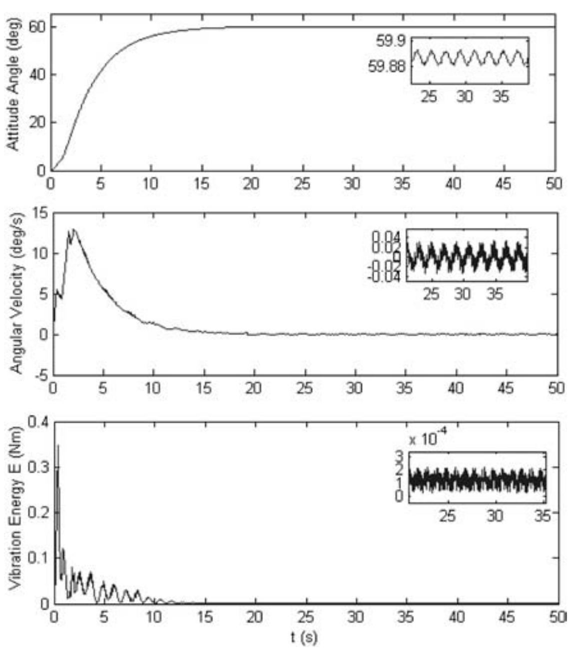


Figure 8 Slew using PD without CSVS method



suppression of the flexible appendages during and after the attitude maneuver.

The second set of simulations includes the three tests:

1. with the active vibration control technique of OPPF control using smart material without the CSVS method;
2. with a second-order robust with four components for the first mode (SORFCFM) and OPPF control; and
3. with a second-order robust with four components for the first mode and zero-order robust with two component for the second mode (SORFCFM and ZORTCSM) and OPPF control.

For a fair comparison, in these three tests, the control parameters (PD gains) for the attitude subsystem remain the same with the first set of simulations and the flexible spacecraft is also commanded to perform a 60° slew. Time histories of attitude angle, angular velocity and the flexible appendages vibration of the spacecraft for the three tests are shown in Figures 9-11 (please notice the differences in scale). In the first case, since the active suppression subsystem is implemented, active damping is provided to the flexible appendages from the PZT patches. No severe vibration is observed in Figure 9 as compared with Figure 8, at steady state, about 0.1 and 0.015°/s period errors for the angle and angular velocity, respectively, in slewing are observed, and the vibration energy level is brought

Figure 9 Slew using PD with OPPF control

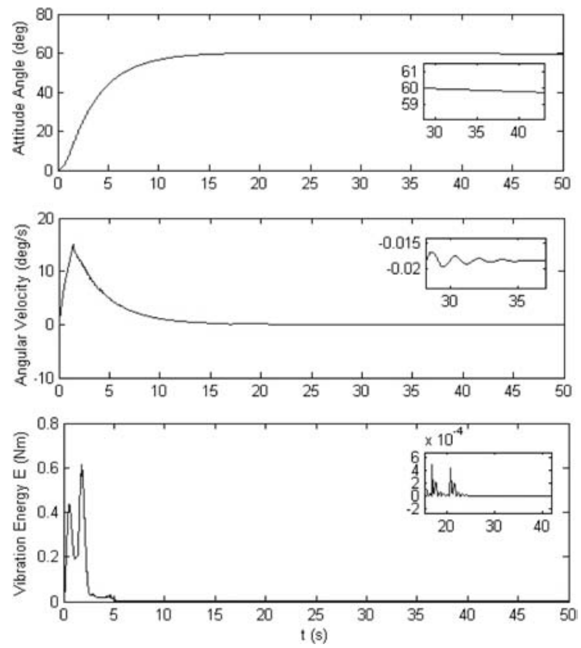


Figure 10 Slew using PD with SORFCFM and OPPF

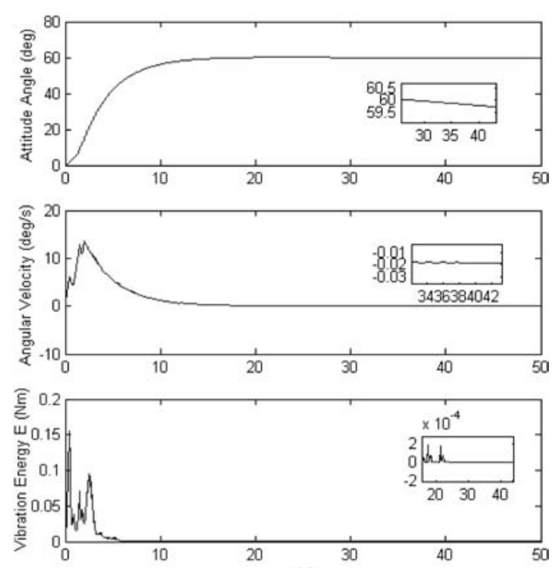
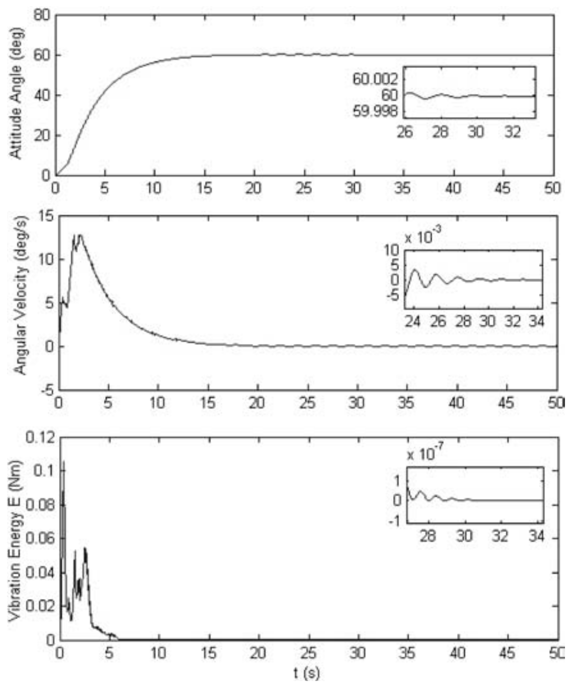


Figure 11 Slew using PD with a SORFCFM and ZORTCSM and OPPF



down to no more than 0.6 Nm as shown in the bottom of Figure 9. In the last two cases, the integrated approach of using CSVS method and OPPF control with the smart materials can significantly improve precision pointing of the spacecraft and dramatically reduce vibrations during 60° slew operation of the flexible spacecraft as shown in Figures 10 and 11. From comparison of Figures 10 and 11, it is clear that, the integrated approach of using CSVS method with a second-order robust with four components for the first mode and zero-order robust with two component for the second mode and OPPF control with the smart materials can offer the most vibration reduction with the maximum amplitude of the vibration energy less than 0.12 Nm. The second set of simulation demonstrates just using the technique of active vibration suppression can effectively reduce the vibrations of flexible appendages after the maneuver, but with severe vibration (big vibration energy) at the beginning because of the limitation of the control capacity, whereas the integration the active vibration control using smart materials with the CSVS method can dramatically reduce vibrations during and after attitude maneuver.

7. Conclusions

In this paper, a new approach for vibration reduction of flexible spacecraft during attitude maneuver is presented. The new approach integrates the method of CSVS and the technique of OPPF control with the smart materials as sensors and actuators. The method of CSVS is used to modify the existing input command so that less vibration will be caused by the command itself. However, considering the on-off thruster actions, the PWPF modulation is used to control thruster firing in the attitude control system to reduce vibrations introduced to the flexible appendage and integrated with CSVS method to obtain the constant amplitude components for the on-off actuators. This combination of the CSVS method and the PWPF modulator can suppress the relatively large amplitude vibrations excited by rapid maneuvers. Nevertheless, some residual micro-vibrations may be present. On the contrary, the technique of PPF control using smart materials as sensors/actuators is more suitable for suppression of micro-vibrations, i.e. fine-tuning the system at the final stage of operations, which is desirable for precision pointing of advanced spacecraft. The OPPF compensator is devised by setting up a cost function to be minimized by feedback gains, which are subject to the stability criterion at the same time, such that an extension to the conventional PPF control design approach is presented. Simulation results of attitude maneuver of a flexible spacecraft with smart material as sensors and actuators demonstrate that with the CSVS method and the PPF compensator, the proposed new approach can significantly reduce the vibration of the flexible appendages during maneuver operations. Future work is planted to study the digital implementation of the control scheme on hardware platforms for attitude control experimentation.

References

Anthony, T., Wei, B. and Carroll, S. (1990), "Pulse modulated control synthesis for a spacecraft", *Journal of Guidance, Control, and Dynamics*, Vol. 13 No. 6, pp. 1014-5.

Fanson, J.L. and Caughey, T.K. (1990), "Positive position feedback control for large structure", *AIAA Journal*, Vol. 28 No. 4, pp. 717-24.

Hari, B.H. (1994), "Multiaxis tracking and attitude control of flexible spacecraft with reaction jets", *Journal of Guidance, Control, and Dynamics*, Vol. 17 No. 4, pp. 831-9.

Hu, Q.L. and Ma, G.F. (2005a), "Variable structure control and active vibration suppression of flexible spacecraft during attitude maneuver", *Aerospace Science and Technology*, Vol. 9 No. 4, pp. 307-17.

Hu, Q.L. and Ma, G.F. (2005b), "Vibration suppression of flexible spacecraft during attitude maneuvers", *Journal of Guidance, Control, and Dynamics*, Vol. 28 No. 2, pp. 377-80.

Hu, Q.L. and Ma, G.F. (2005c), "Maneuvers and vibration suppression of flexible spacecraft with input nonlinearities", *Aircraft Engineering and Aerospace Technology*, Vol. 75 No. 5, pp. 388-400.

Hu, Q.L. and Ma, G.F. (2006), "Maneuvers and vibration suppression of flexible spacecraft integrating variable structure control and input shaping technique", *Transactions of the Japan Society for Aeronautical and Space Sciences*, Vol. 48 No. 162, pp. 205-12.

Jun, J., Shan, J.J., Sun, D. and Liu, D. (2004), "Design for robust component synthesis vibration suppression of flexible structures with on-off actuators", *IEEE Transactions on Robotics and Automation*, Vol. 20 No. 3, pp. 512-25.

Shan, J.J. (2002), "Study on CSVS method for the flexible spacecraft", PhD thesis, Harbin Institute of Technology.

Sighose, W., Banerjee, A. and Seering, W. (1990), "Slewing flexible spacecraft with deflection-limiting input shaping", *Journal of Guidance, Control, and Dynamics*, Vol. 20 No. 6, pp. 1014-5.

Singer, N. and Seering, W. (1990), "Preshaping command inputs to reduce system vibration", *Transactions of the ASME Journal of Dynamic Systems, Measurement and Control*, Vol. 112 No. 1, pp. 76-82.

Song, G. and Agrawal, B.N. (2001), "Vibration suppression of the flexible spacecraft during attitude control", *Acta Astronautica*, Vol. 49 No. 2, pp. 73-83.

Song, G., Buck, N. and Agrawal, B. (1999), "Spacecraft vibration reduction using pulse-width pulse-frequency modulated input shaper", *Journal of Guidance, Control, and Dynamics*, Vol. 22 No. 3, pp. 433-40.

Vander Velde, W. and He, J. (1983), "Design of space structure control systems using on-off thrusters", *Journal of Guidance, Control, and Dynamics*, Vol. 6 No. 1, pp. 430-6.

Wie, B. and Plescia, C.T. (1984), "Attitude stabilization of flexible spacecraft during station-keeping manuevers", *Journal of Guidance, Control, and Dynamics*, Vol. 7 No. 4, pp. 430-6.

About the author

Qinglei Hu received the BS, MS, and PhD degrees from the Zhengzhou University, Zhengzhou, Chian, in 2001, Harbin Institute of Technology, Harbin, China, in 2003, and Harbin Institute of Technology, Harbin, China, in 2006, respectively, all in the electrical engineering. In 2003, he joined the Harbin Institute of Technology, Harbin, China, where he is now a Lecturer. He is the Member of The Japan Society for Aeronautical and Space Science. His current research interests include variable structure control and application, robust control and application, active vibration control, spacecraft attitude control, and fuzzy control and application. E-mail: huqinglei@hit.edu.cn, huqinglei@126.com and hithuqinglei@yahoo.com