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A Hybrid Scheme of Feed-forward/Feedback Control for Vibration Suppression of Flexible Spacecraft with On-Off actuators during Attitude Maneuver

QINGLEI HU[1], YAQIU LIU[2]

[1] Harbin Institute of Technology, No.92, West Da-Zhi Street, Harbin 150001, China
huqinglei@hit.edu.cn

[2] Northeast Forestry University, He-xing Road, Harbin 150001, China
yqliu@hit.edu.cn

Abstract

This investigation is to apply the so-called component synthesis vibration suppression (CSVS) based feed-forward control and the conventional PD feedback control to the vibration control of a flexible spacecraft. The proposed control design process is two fold: design of the attitude controller followed by the design of a flexible vibration attenuator, the feed-forward controller. The Lyapunov technique is applied in the design of the attitude controller, which is able to asymptotically stabilize the flexible spacecraft system. The feed-forward controller based on CSVS method is designed for the reduction of flexible vibration by modifying the command input, which only requires information about the natural frequency and damping of the closed-loop system including the attitude controller. Additionally, to extend the CSVS method to the system with the on-off actuators, the pulse-width pulse-frequency (PWPF) modulation is introduced to control the thruster firing and integrated with the CSVS method. PWPF modulation is a control method that provides pseudo-linear operation for an on-off thruster. The proposed control strategy has been implemented on a flexible spacecraft, which is a hub with symmetric cantilever flexible beam appendage and can undergo a single axis rotation. The results have been proven the potential of this technique to control flexible spacecraft.

Keyword: vibration suppression, attitude maneuver, flexible spacecraft, pulse-width pulse-frequency (PWPF), component synthesis vibration suppression (CSVS)

I. Introduction

Vibration reduction is a critical problem related to the maneuvering of modern spacecrafts, which use large, complex, and light weight space structures, such as solar array panels, to achieve increased functionality at a reduced launch cost, but results in the spacecraft being extremely flexible and having low fundamental vibration modes.

Research in this area has been under taking along two directions: one direction concentrates on seeking efficient methods to convert continuous input to on-off signals suitable for controlling on-off thrusters, and the other focuses on modifying an existing command so that it results in less or zero residual vibration of a FS. Research toward thruster control has been focused on mainly two areas: bang-bang control and pulse modulation in [1-6]. Bang-bang control is simple in formulation, but results in excessive thruster action. Its discontinuous control actions may interact with the flexible modes of spacecraft and result in limit cycles. On the other hand, pulse modulators are commonly employed due to their advantages of reduced propellant consumption and near-linear duty cycles.

Pulse modulators such as pseudo-rate modulator in [2], integral-pulse frequency modulator[3], and pulse width pulse frequency (PWPF) modulator [4,6] have been proposed. Among these, the PWPF modulator holds several superior advantages such as close to linear operation, high accuracy, and adjustable PWPF that provide scope for advanced control. This modulator was used on several spacecraft such as the Agena satellite, INTELSAT-5, INSAT and ARABSAT.

Command shaping techniques are another possible solution to that problem. Set of command shaping technique also exists, such as input shaping [6-9], and component synthesis vibration suppression (CSVS) method [10-13]. These techniques work by altering the shape of either the actuator commands or the reference outputs, to reduce the oscillation of the system response. There are several superior advantages for these two methods, including effectiveness in vibration cancellation, robustness to vibrations in modal frequency and damping ratio, and suitability for a multi-modes system. Input shaping refers to a particular command shaping technique that exploits the convolution of the reference signal with a sequence of impulses (input shapers) to reduce the system vibrations. For CSVS method, it was first proposed by Liu et al. in [9,10] for implementation of rendezvous and docking of flexible structures, which can eliminate unwanted flexible modes of vibration while achieving the desired rigid body motion. By increasing robustness, the robust CSVS method is proposed and fully analyzed in [13]. The major difference between input shaping and the so-called CSVS method lies in the design of input commands. Input shaping employs numerical optimization to derive an input shaper and then convolve it with the reference command. Note that the input shapers were obtained based on relatively complicated numerical calculations, in which simultaneous nonlinear equations are involved. By contrast, the CSVS method uses analytic methodology to derive the input commands, without solving nonlinear equations. It is obvious that the CSVS method is simpler and more intuitive than input shaping. Moreover, the CSVS commands can be of many forms. Originally, CSVS method was designed for systems with proportional actuators [10-12]. Recently, it has been extended to systems with on-off actuators in Ref. [13]. However, existing approaches require complicated non-linear optimizations and sometimes result in bang-bang control action.

It should be noted that the CSVS method is a feed-forward control technique and has been mainly considered for the open loop system in [10-13]. Feed-forward techniques for vibration suppression involve developing the control input through consideration of the physical and vibrational properties of the system, so that system vibrations at response modes are reduced. This method does not require any additional sensors or actuators and does not account for changes in the system once the input is developed. But there is no robustness to external disturbances and fail to give an appropriate answer to parameter uncertainty. However, feedback controllers, can be designed to overcome these drawbacks. Considerable work has been done as feedback control strategies for maneuver control of flexible spacecraft in [14-16].

In this paper, a hybrid control scheme of feed-forward control based on CSVS method and feedback control is proposed for vibration reduction of flexible spacecraft during maneuver operation. The general control structure of closed-loop with CSVS method is shown in Figure 1. The benefit of using this combination is made evident by the reduction in vibration of the flexible appendage and satisfies the performance requirement of the closed-loop system. The proposed control design process is two fold: design of the attitude controller and then design of a flexible vibration controller based on the CSVS method for the closed-loop system. The attitude controller design does not need the knowledge of modal variables and just requires the attitude and rate information. The Lyapunov method is applied in the design of this controller such that the closed-loop system is asymptotically stable. The CSVS method can eliminate the unwanted flexible modes of vibration while achieving the desired attitude motion by modifying the existing command, which only requires information about the natural frequency and damping of the closed-loop system. In addition, to extend the CSVS method to system with on-off thruster actuator mode, a scheme of integrating CSVS method with a PWPF modulation is given, which do not require the complicated non-linear optimizations to design the constant amplitude input commands for the system with on-off actuators. There are several major benefits from this integration: from a practical standpoint, multiple-mode robust and variable amplitude component sequences are easily obtained. High value of vibration suppression should be available without incurring excessive maneuver time penalties. The controller can be modified real-time in the presence of varying plant condition. Finally, if operation of the PWPF modulator is sufficiently linear, high–frequency vibration entrained during the slew maneuvers can also be effectively reduced. Numerical simulations performed on a two-mode model of the spacecraft with flexible appendages during rest-to-rest maneuver demonstrate the effect and feasibility of the method.

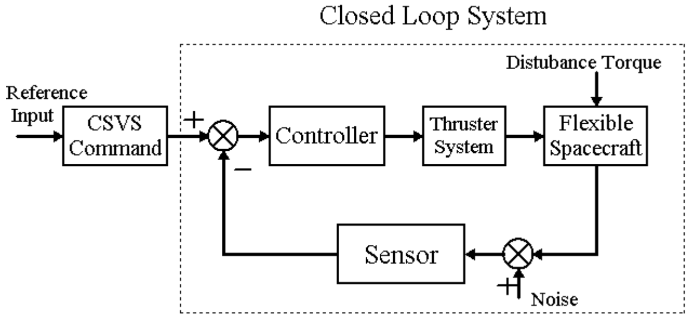


Fig.1 Block Diagram of a System Using component synthesis vibration suppression (CSVS) method

II. Mathematical Model

The spacecraft model configuration is shown in Fig.2.

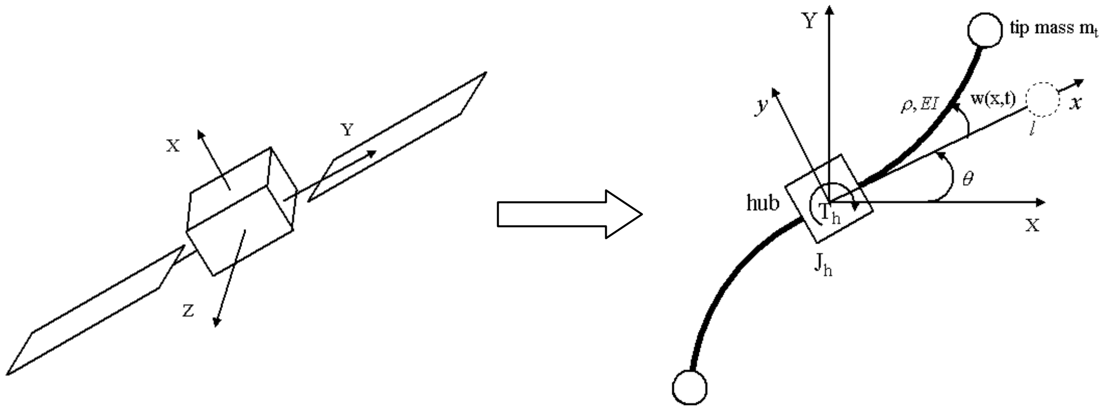


Fig.2 Spacecraft model with single-axis rotation

Symmetric flexible appendages, such as solar arrays, are attached to the center body. The center body is subject to a single-axis rotational motion θ. The control torque T_h is applied to the center body. The solar arrays tend to vibrate due to the coupling effect with the rigid body rotation. They are simplified as flexible beams with tip masses. The solar array flexibility is reflected into the beam, and the frequencies of oscillation are tuned by the tip masses. It is assumed that two solar arrays are identical in geometric and material properties. Under the torque control input only to the center body, the deflection of each solar array should be identical. Namely, the deflection takes place in an anti-symmetric fashion.

The original governing equations of motion for the spacecraft model are given by [10-12]

$$J_h\ddot{\theta} + 2\int_b^l \rho x(x\ddot{\theta} + \tfrac{\partial^2 w}{\partial t^2})dx + 2m_t l(l\ddot{\theta} + \tfrac{\partial^2 w}{\partial t^2}\big|_l) = T_h$$
$$\rho(x\ddot{\theta} + \tfrac{\partial^2 w}{\partial t^2}) + EI\,\tfrac{\partial^4 w}{\partial x^4} = 0 \tag{1}$$

where J_h is moment of inertia of the center body, m_t is tip mass, ρ and EI are the linear mass density and elastic rigidity of the flexible beams. Furthermore, $w(x,t)$ represents deflection of the flexible beams, b represents radius of the center body, and l is the distance from the middle of the center body to the tip masses. Flexible arm dynamics also subjected to tip boundary conditions at the root and tip of the beam such as

$$w(x,t) = \tfrac{\partial w(x,t)}{\partial t} = 0 \qquad \text{at } x = b$$
$$\left.\begin{aligned} &EI\,\tfrac{\partial^2 w(x,t)}{\partial t^2} = 0, \\ &EI\,\tfrac{\partial^3 w(x,t)}{\partial t^3} = m_t(l\ddot{\theta} + \tfrac{\partial^2 w(x,t)}{\partial t^2}) \end{aligned}\right\} \text{at } x = l \tag{2}$$

The original hybrid differential equations of motion equation (1) can be discretized into a finite dimensional mathematical model. The mathematical model is developed for simulation study and the model-based control law design. The deflection of the flexible beam can be approximated as

$$w(x,t) = \sum_{i=1}^{\infty} \phi_i(x) q_i(t) \tag{3}$$

where $\phi_i(x)$ $(i = 1, 2, \ldots)$ are shape functions to be obtained by solving a characteristic equation for a cantilevered beam problem, and $q_i(t)$ are the generalized coordinates for the flexible deflection.
Finite dimensional approximation with the shape functions obtained can be applied to derive discrete equations of motion by Largange's method. The linearized second order matrix form of the differential equations of motion can be written as

$$J\ddot{\theta} + M_{\theta q}\ddot{q} = T_h \tag{4a}$$

$$M_{\theta q}^T\ddot{\theta} + M_{qq}\ddot{q} + K_{qq}q = 0 \tag{4b}$$

where $q = [q_1, q_2, \ldots]^T$, and the element mass and stiffness matrices are governed by

$$J = J_h + 2\int_b^l \rho x^2 dx + 2m_t l^2\,, M_{\theta q} = 2\int_b^l \rho x\phi_i(x)dx + 2m_t l\phi_i(l)\,, M_{qq} = \int_b^l \rho\phi_i(x)\phi_j(x)dx + m_t\phi_i(l)\phi_j(l)\,,$$

$$K_{qq} = \int_b^l EI\phi_i''(x)\phi_j''(x)dx\,.$$

Considering the flexible space structure as shown in Fig.2, the objective of the slew maneuver of this study is a rest-to-rest maneuver, and the whole structure is rotated about the vertical axis from a rest state to another rest state in the shorts time possible. The angle $\theta(t)$ is rotated from initial state to $\theta_d \in [0, 2\pi]$, for example, setting to 120deg throughout this study. The sensor output available for the output feedback is hub angle θ and angular rate $\dot{\theta}$, and no state estimator is involved. Based on the customarily requirements of flight task of actual spacecraft, control scheme should also satisfy the following dominating demands: Short transient time, no overshooting or less overshooting, and high precision, and less vibration stirred; Strong capability to resist disturbance of vibrations in both transient process and steady state.

III. Control Strategies

A. *Principle of Component Synthesis Vibration Suppression (CSVS)*

The component synthesis vibration suppression (CSVS) method was first put forward in 1987 in [10]. It 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 founded in [10-13] in detail.
Considering the following equation (5), which is a generalized vibration system.

$$\ddot{z} + 2\varsigma\omega\dot{z} + \omega^2 z = F(t) \tag{5}$$

where z is the state coordinate, 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 $T_d = 2\pi / \omega_d$. Fig.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 $Ae^{-\pi\varsigma\sqrt{1-\varsigma^2}}$. Ideally, no vibration exists after such superimposition.

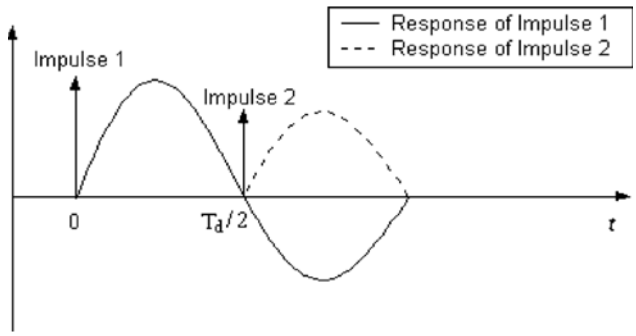


Fig.3 Basic principle of (CSVS) method

Fig.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 component synthesis vibration suppression (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 $0, T_d / n, \cdots, (n-1)T_d / n$ leads to suppression of this vibration mode completely. 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.

B. *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 [11]. 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 1. Given that the response of system (5) caused by an input command is $Z(t)$, and the end time instant of the input command is t_f ,if $Z(t>t_f)=0$, $\partial Z(t>t_f)/\partial\omega\big|_{\omega_m}=0$, $\partial^2 Z(t>t_f)/\partial\omega^2\big|_{\omega_m}=0$, … , $\partial^n Z(t>t_f)/\partial\omega^n\big|_{\omega_m}=0$ and $\partial^{n+1} Z(t>t_f)/\partial\omega^{n+1}\big|_{\omega_m}\neq 0$,then the input command is stable to suppress the vibration and with the n^{th}-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 p^{th}-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+1th-order robustness to the frequency error.

Remark 1. The robustness to uncertainty of the damping ratio can be analyzed in a similar manner, since the derivative of the system response with respect to the frequency has the same expression as that with respect to damping ratio.

C. *Suppression of Multimode Vibrations*

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 n^{th} vibration mode, can suppress all the n vibration modes.

According to Lemma 1, Lemma 2, and Lemma 3, various CSVS commands can be constructed, with any number of components n, any order of robustness and any multiple modes.

Remark 2. 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.

D. *PD Feedback Control*

PID control is commonly used in most satellite attitude control system. This is due to the fact that PID is effective, simple for implementation, and robust against system's uncertainties. In this section, this control method is reinvestigated with a new possible capability for the vibration suppression of flexible spacecraft.

Considering the following PD control for the attitude control system

$$T_h=-K_p(\theta-\theta_f)-K_d\dot{\theta} \qquad (6)$$

where θ_f is the desired angle to be reached, the design parameters $K_p, K_d > 0$.

By substituting the control law (6) into the flexible spacecraft dynamics (4), the closed-loop dynamics is given by

$$M\begin{bmatrix}\ddot{\theta}\\ \ddot{q}\end{bmatrix}+K\begin{bmatrix}\theta\\ q\end{bmatrix}=\begin{bmatrix}-K_p(\theta-\theta_f)-K_d\dot{\theta}\\ 0\end{bmatrix} \tag{7}$$

where $M=\begin{bmatrix}J & M_{\theta q}\\ M_{\theta q}^T & M_{qq}\end{bmatrix}, K=\begin{bmatrix}0 & 0\\ 0 & K_{qq}\end{bmatrix}$

Theorem 1. Given the dynamics as described by equation (4), let the control law be computed as equation (6), then the equilibrium state of its closed-loop system (7) is globally asymptotical stable, i.e., $\theta \to \theta_f$, and $\dot{\theta}, q, \dot{q} \to 0$ as time $t \to \infty$.

Proof: Consider the energy-based Lyapunov function

$$V=\frac{1}{2}\begin{bmatrix}\dot{\theta}\\ \dot{q}\end{bmatrix}^T M\begin{bmatrix}\dot{\theta}\\ \dot{q}\end{bmatrix}+\frac{1}{2}q^TK_{qq}q+\frac{1}{2}e^TK_pe\geq 0 \tag{8}$$

where $e=\theta-\theta_f$. $V=0$ only at the system equilibrium state, i.e., $\theta=\theta_f, \dot{\theta}=0$ and $q=\dot{q}=0$. The time derivative of Lyapunov function along the trajectories of the closed-loop system is

$$\begin{aligned}\dot{V}&=\begin{bmatrix}\dot{\theta}\\ \dot{q}\end{bmatrix}^T M\begin{bmatrix}\ddot{\theta}\\ \ddot{q}\end{bmatrix}+\dot{q}^TK_{qq}q+\dot{e}^TK_pe\\ &=-\dot{\theta}^T(K_pe+K_d\dot{e})+\dot{e}^TK_pe=-\dot{\theta}^TK_d\dot{\theta}=-K_d\dot{\theta}^2\leq 0\end{aligned} \tag{9}$$

where $\dot{e}=\dot{\theta}-\dot{\theta}_f=\dot{\theta}$.

At this stage, it can only be concluded that under the PD control, the system energy does not increase. This is the so-called global stability in the sense of Lyapunov. To prove asymptotically stable, it has to be shown that $\dot{V}=0$ only at the system equilibrium state. As K_d is positive, $\dot{V}=0$ only when $\dot{\theta}=0$. Invoking LaSalle [17] invariance set theorem, one can see that the equilibrium state of the system is globally asymptotically stable.

Remark 3. It is noted that this PD control only feeds back the attitude angle θ and angular rate $\dot{\theta}$, and does not require any information of the modal vibration. It is a model-independent feedback control and robustness against model uncertainties

IV Pulse-Width Pulse-Frequency (PWPF) Modulation

In this research, a PWPF modulation is used to control the on-off thrusters for attitude maneuver. The PWPF modulated thruster control has been shown to excited fewer modal vibrations than bang-bang controller in Ref. [6], which can be considered as a passive means for vibration reduction. The PWPF modulator produces a pulse command sequence to the thruster by adjusting the pulse width and pulse frequency. In its linear range the average torque produced equals the demanded torque input. As shown in Fig.4, the PWPF modulator [4,6] is composed of a Schmidt Trigger, a pre-filter, and a feedback loop.

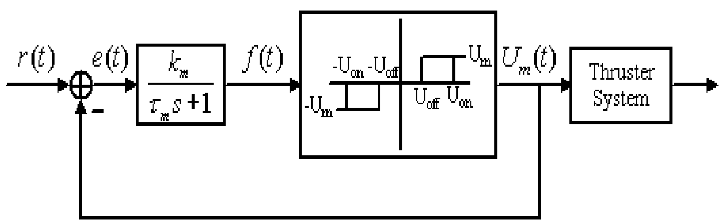


Fig.4 pulse-width pulse-frequency (PWPF) modulator

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 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. The pulse width pulse frequency 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 flexible spacecraft attitude controls. Due to nonlinear nature of the modulator, analytic methods such as describing function cannot produce accurately prediction over a large operation range. Instead, extensive numerical simulations have been carried out to study the effects of these parameters on the performances of the modulator. This paper only presents results from the numerical studies and details on PWPF parameter selection can be founded in [6]. The preferred range of parameters through extensive simulations is listed in Table1.

Table 1. Recommended range of PWPF parameters

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}	$U_{off}<0.8Uon$	N/A	$U_{off}<0.8U_{on}$
U_m	N/A	0.5	0.5

To better understand PWPF modulation, Fourier transform of the output of a PWPF modulator in pseudo-linear operation is also performed and compared with that of the input of sinusoidal signal, as shown in Fig.5. This figure indicates some minor frequency components in the PWPF output besides the main component (input frequency). Even if the PWPF modulator does not exactly replicated the input command frequency, these extra frequency components generated by a PWPF modulator must be taken into consideration when it is used to modulate the command input.

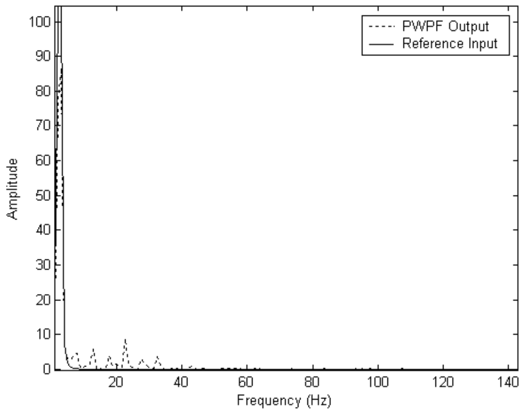


Fig.5 Power spectral density plots

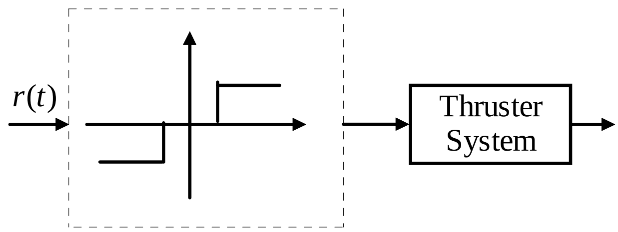


Fig.6 Bang-bang control with dead-zone

On the other hand, bang-bang controller can also be used to convert a continuous signal to an on-off type signal that is suitable for thruster control. A bang-bang controller with dead-zone shown in Figure 6 is to use in this paper to reduce the number of thruster firings and fuel consumption at a possible cost of control accuracy. The effect of PWPF modulation will be compared with that of dead-zoned bang-bang control.

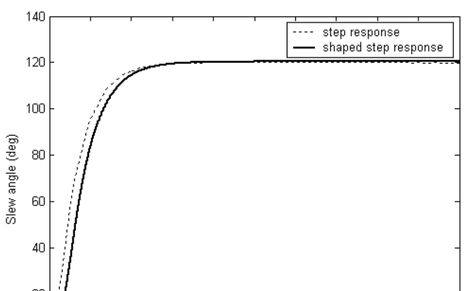
V. Simulation Results

To demonstrate the effectiveness of the proposed control schemes, numerical simulations have been performed and presented in this section. The numerical model of the spacecraft is from the Ref. [13]. Because low-frequency modes are generally dominant in a flexible system, in this paper, the first two modes frequency 3.161rad/s and 16.954rad/s, respectively, are major concerns for vibration suppression.

The CSVS technique consists of selecting an appropriate sequence components that have the desired robustness for the system that is to be controlled. As shown in Section 2, to enhance the robustness of CSVS method, higher-order robust with more components can be used. Nevertheless, with the increase of the robustness, the command shaping will resulted in slower rigid-body response. Therefore, considering the trade-off between increasing robustness and the rigid-body response speed, second-order robust with four components for the first mode and zero-order robust with two component for the second mode are used in the process of simulation for the multi-mode flexible system.

The PWPF modulator parameters are selected as $k_m = 3$, $\tau_m = 0.15$, $U_{on} = 0.4$, $U_m = 0.5$ and $U_{off} = 0.15$, respectively, based on recommendations from Table 1 and extensive numerical simulations trials.
In this simulation, the flexible spacecraft is commanded to perform a 120^o slew. For comparative purposes, four different cases of a 120^o slew of the flexible spacecraft are conducted: (1) slew using PWPF modulation with CSVS method; (2) slew using PWPF modulation without CSVS method; (3) slew using dead-zoned bang-bang control with CSVS method; (4) further study the robustness of CSVS method. Case (1) is compared with case (2) to show the effectiveness of active vibration suppression of thruster firing induced vibration using CSVS method during the attitude control. On the other hand, case (1) is compared against case (3) to demonstrate the advantages of PWPF modulation for attitude control over bang-bang control with dead-zone. Last case shows the robustness of CSVS method for the frequencies within ±20% error.

First, to demonstrate the effect of the active vibration suppression using the CSVS method, the PWPF modulator is employed in the attitude control system to slew the flexible spacecraft for 120^o with the eight shaped components command. The angular displacement of the rigid body along with first two modes vibrations are shown in Fig.7-Fig.9. Then the same control parameters for the attitude control system is repeated with just step command replacing the eight shaped components command using, and the results are also shown in Fig.7~Fig.9. It is clear that, from comparison of the Fig.8~Fig.9, the first two modes vibrations are more severe and the maximum amplitude is 0.3m when unshaped step command is used. However, using a shaped eight-component command with the PWPF modulator results in excellent cancellation of the targeted modes. Reductions in modal excitations of up to 90% are achieved in the first two modes. This shows the effectiveness of the CSVS method for active vibration suppression of the flexible appendage.



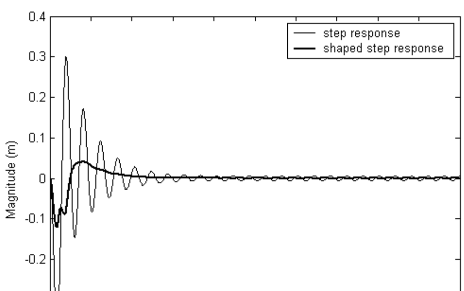


Fig.7 Step command and shaped step command with PWPF modulator

Fig.8 The first modal displacement η_1 with PWPF modulator

The case of bang-bang control with dead-zone is employed to in the attitude control system to slew the flexible spacecraft for 120^{o} with the eight shaped components command. The dead-zone is set from -0.4 to +0.4, which corresponds to the data for the PWPF modulator. The same control parameters for the attitude control system are remained for comparison. The vibrations of rigid body and flexible appendage are reflected in Fig.10 and Fig.11. As compared with Fig.7~Fig.9, when bang-bang control with dead-zone is used, severe rigid body and flexible appendage interaction is observed. This reflects the advantages of PWPF modulation over bang-bang control with dead-zone.
To further study the robustness of the CSVS method, consider that in practice modal frequency generally can be obtained to within ±20% error. The simulation is run with ±20% error in the first modes with that of exactly known modal frequency. The rigid-body response is shown in Fig.12 and the first mode response is shown in Fig.13. Fig.12 reveals that error in modal frequency slightly changes the setting time; however, it is has little impact on the final stage error. Fig.13 shows that the case of +20% frequency error is very close to the nominal case, whereas the case -20% frequency error has a slightly increased vibration. Either case is robust with error in modal frequency. Mode 2 shows the same trend (figures not shown because of space limitation).

In summary, the benefit of using this combination of feed-forward and feedback control is made evident by the reduction vibration of the flexible appendage and satisfies the performance requirement of the closed-loop system. Integrating the techniques of CSVS and PWPF modulation provides a simple, effective and robust method to suppress vibration of flexible spacecraft.

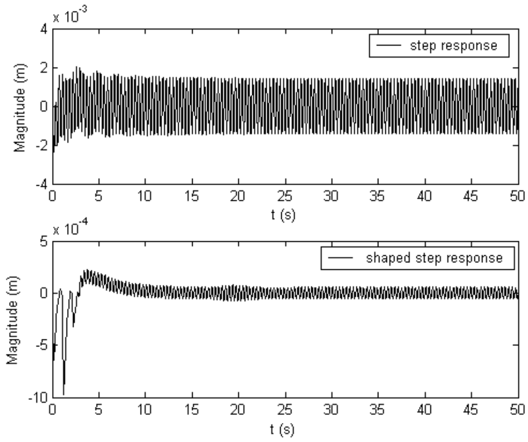


Fig.9 The second modal displacement η_2 with PWPF modulator

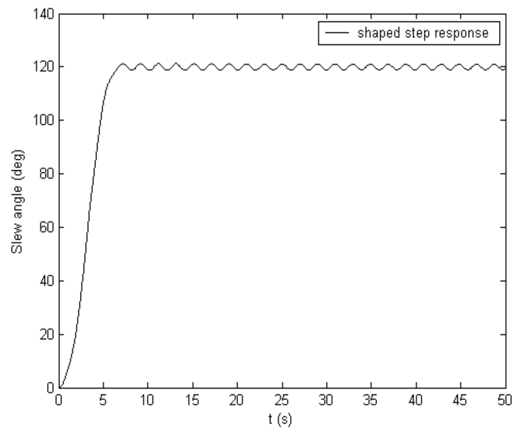
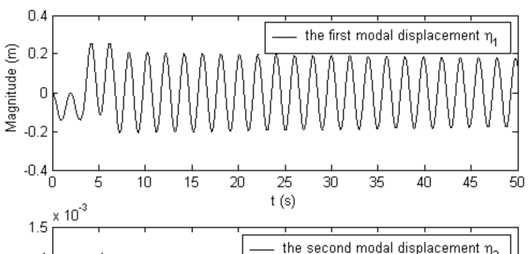


Fig.10 Shaped step command with dead-zoned bang-bang control



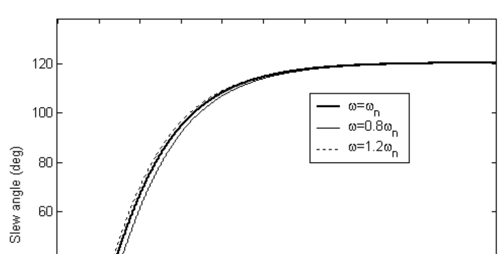


Fig.11 The first two modal displacement η_1 and η_2 with dead-zoned bang-bang

Fig.12 Rigid-body response with ±20% modal frequency uncertainty

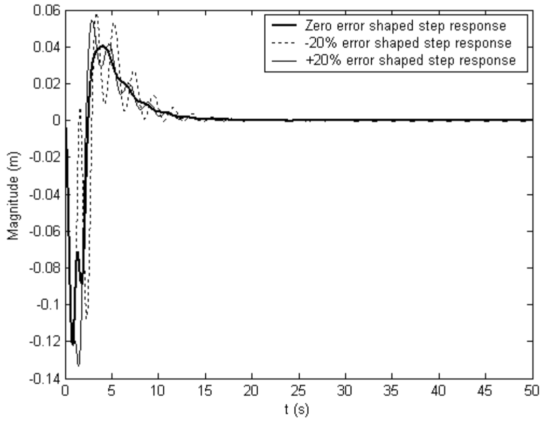


Fig.13 The first modal displacement for ±20% modal frequency uncertainty

VI. Conclusions

This paper presents the first study of a PWPF modulated thruster control using the technique of component synthesis vibration suppression (CSVS) based command shaping for the vibration suppression and attitude control of a flexible spacecraft during attitude maneuver. The attitude controller was designed for the flexible spacecraft based on Lyapunov technique to satisfy the performance requirement of the closed-loop system, which is computational simplicity and straightforward tuning. The CSVS method was employed to actively suppress vibrations induced by modifying the command input, which does not affect the stability of the closed loop system in any way, and simply modifies the command signal to the system. Considering the on-off thruster actuators, a new approach integrating a PWPF modulator with CSVS method is applied to computer simulations of rest-to-rest attitude maneuvers of a satellite with flexible appendage. As compared with several differences methods, performances of the techniques have been evaluated in terms of level of vibration reduction, speed of the response, and robustness through.

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QINGLEI HU received the B.S. and M.S. degrees from the Zhengzhou University, Zhengzhou, Chian, in 2001, and Harbin Institute of Technology, Harbin, China, in 2003, respectively, all in the electrical engineering. He is currently pursuing the Ph.D. degree in Control Science and Engineering form Harbin Institute of Technology.
In 2003, he joined the Harbin Institute of Technology, Harbin, China, where he is now a Lecture. He is the Student Member of The Japan Society for Aeronautical and Space Science. His current research interests include variable structure control & application, robust control & application, active vibration control, spacecraft attitude control, and fuzzy control & application.

YAQIU LIU received the Ph.D. degree from Harbin Institute of Technology, Harbin, China, in 2004. He is currently a professor with Northeast Forestry University, Harbin, China. His current research interests include adaptive inverse control, active vibration control, and spacecraft attitude control.