Vibration Reduction for Flexible Spacecraft Attitude Control using PWPF Modulator and Smart Structures

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Abstract—This paper presents a new approach to vibration reduction of flexible spacecraft during attitude control by using Pulse Width Pulse Frequency (PWPF) Modulator for thruster firing and smart materials for active vibration suppression. The experiment was conducted on the Naval Postgraduate School (NPS)'s Flexible Spacecraft Simulator (FSS), which consists of a central rigid body and an L-shape flexible appendage. A pair of on-off thrusters are used to re-orient the FSS. To actively suppress vibrations introduced to the flexible appendage, embedded piezoelectric ceramic patches are used as both sensors and actuators to detect and counter react to the induced vibration. For active vibration suppression using the piezoelectric ceramic patches, Positive Position Feedback (PPF) control targeting at the first two flexible modes of the FSS system is used. Experimental results demonstrate the effectiveness of the control strategy of PWPF modulation for attitude control and PPF for active vibration suppression.

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1. INTRODUCTION

Modern spacecraft often employ large flexible structures such as solar arrays, meanwhile requirement for attitude control performance becomes more stringent. For attitude operations that require small control actions, reaction/momentum wheels are used. However, during orbital correction maneuvers, such as north-south station keeping and slew, the required torque are normally too high for reaction/momentum wheels. Therefore, thrusters are normally used for attitude control during these maneuvers.

Reaction/momentum wheels can provide continuous control action according to the desired torque profile for attitude control. Thrusters, on the other hand are on-off devices and normally capable of providing only fixed torque. Therefore, achieving high attitude control performance using thrusters is a challenging task. The task becomes even more complicated for flexible spacecraft where thruster firings could excite flexible modes resulting in attitude control instability or limit cycles.

The two major approaches for thruster control are bangbang control and pulse modulation. Bangbang 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 cycle. In general, pulse modulators produce a pulse command sequence to the thruster valves by adjusting pulse width and/or pulse frequency. Pulse modulators such as pseudo-rate modulator (Millar and Vigneron, 1976), integral-pulse frequency modulator (Clark and Franklin, 1969; Hablani, 1994), and Pulse-Width and Pulse-Frequency (PWPF) modulator (Bittner, 1982; Wie and Plescia, 1984; Anthony et al, 1990; Song, et al, 1998a) have been proposed. Among these, the PWPF modulator holds several superior advantages such as close to linear operation, high accuracy and adjustable pulse-width and pulse-frequency that provide scope for advanced control.

On-off thruster firing, no matter the method of modulation, will introduce vibrations to the flexible structures to some degree. Effectively suppressing the induced vibration poses a challenging task for spacecraft designers. One promising method for this problem is to use embedded piezoelectric materials as actuator (compensator) since piezoelectric materials have the advantages of high stiffness, light weight, low power consumption and easy implementation. A wide range of approaches have been proposed for using piezoelectric material to actively control vibration of flexible structures. Positive position feedback (PPF) [Goh and Caughey, 1985; Fanson and Caughey, 1990; Agrawal and Bang, 1994; Meyer, et al, 1997] was applied by feeding the structural position coordinate directly to the compensator and the product of the compensator and a scalar gain positively back to the structure. PPF offers quick damping for a particular mode. PPF is also easy to implement. Analytical and experimental study also demonstrate that PPF possesses robustness to variations in modal frequency [Song, et al, 1998b].

The goals of this research are to propose a new approach to vibration reduction of flexible spacecraft, by using PWPF modulation for attitude control and smart structures for active vibration suppression, and to experimentally study the effect of this new approach on vibration reduction of spacecraft during attitude maneuvers. The experimental object of this research is the Naval Postgraduate School's Flexible Spacecraft Simulator (FSS), which is comprised of a rigid central body with on-off type thrusters and a "L"-shape flexible appendage with smart sensors and a smart actuator. The simulator can be fully floated using compressed air and can simulate the motion of a spacecraft about its pitch axis. This paper presents the results of vibration reduction during attitude control of the FSS using PWPF modulation for thruster control and smart structures for active vibration suppression. In this research, a PWPF modulation is used to control the on-off thrusters for attitude maneuver to reduce vibrations introduced to the flexible appendage. This can be considered as a passive means for vibration reduction. Meanwhile, a smart sensor and a smart actuator with PPF control are used to actively suppress vibrations introduced to the flexible appendage by thruster firings. The rest of the paper is organized as follows: Section 2 discusses the FSS setup, including the thrusters, smart structures, vision server system, and the digital data acquisition and real-time control system. Section 3 presents basics about the PWPF modulator. Section 4 introduces the smart structures used in this research and positive position feedback (PPF) control. Section 5 describes the overall control system, which includes two sub-systems: the attitude control sub-system and the active vibration suppression sub-system. Section 6 presents and analyzes the experimental results. Section 7 concludes the paper.

2. The Flexible Spacecraft Simulator

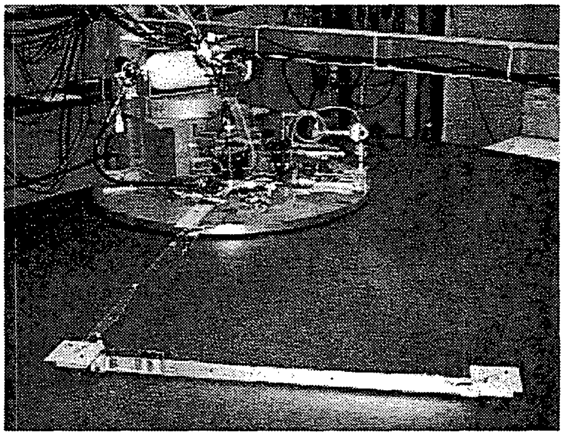

Fig.2.1 The Flexible Spacecraft Simulator (FSS) at U.S. Naval Postgraduate School

The Flexible Spacecraft Simulator (FSS) simulates motion about the pitch axis of a spacecraft. As shown in Fig.2.1, it is comprised of a rigid central body and a "L"-shape flexible appendage. The center body represents the main body of the spacecraft while the flexible appendage represents a flexible antenna support structure. The flexible appendage is composed of a base beam cantilevered to the main body and a tip (remote) beam connected to the base beam at a right angle with a rigid elbow joint. The rigid body is supported by three air pads and the flexible appendage is supported by one air pad each at the elbow and tip. These air pads are used to minimize friction. A finite element model and experiments reveal that the first two modes are dominant modes for this flexible structure and they are major concerns for vibration reduction. The 1^{st} mode is at 0.30Hz and the 2^{nd} mode is at .93Hz.

Measurement of the structure states is accomplished by a full complement of sensors. A rotational variable differential transformer (RVDT) mounted on the center axis of the main body measures angular position. Fig. (2.2) shows piezoceramic patches mounted at the root of the base beam and tip beam to measure strain in the flexible appendage. An optical infrared sensing system, as shown in Fig. (2.3), provides position and rate information for designated LED targets mounted on the structure. Groups of targets are mounted on the main body in addition to the elbow joint and tip of the flexible appendage. This camera is mounted 1.9 meters above the granite table assembly. The camera is connected to a 68030 microprocessor running a real-time operating system, *VxWorks*. The twelve bit digital data obtained by the camera is ported out of the 68030 via a digital-to-analog converter card at 60 Hz sampling frequency. The camera's resolution is nominally at the sub-pixel level on the order of $1/20^{th}$ of a pixel that leads to a camera accuracy of approximately 0.5mm.

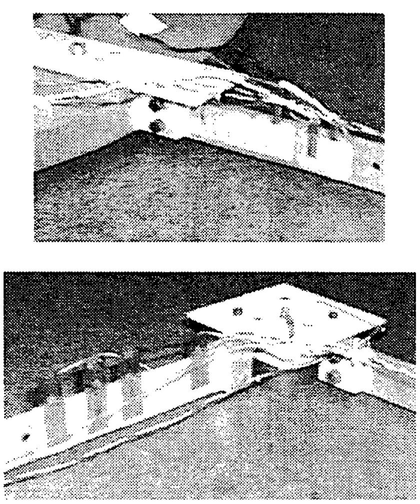

Fig. 2.2. Base joint (upper) and Elbow joint (lower) with Piezoceramic Actuator and Sensor Patches and LED Targets

Two flight qualified cold gas jet thrusters shown in Fig. (2.4) are mounted on the main body of the structure to provide high control authority. The two thrusters are on-off types. Located alongside the piezoceramic sensor patches are actuator patches used to provide active damping to the flexible appendage.

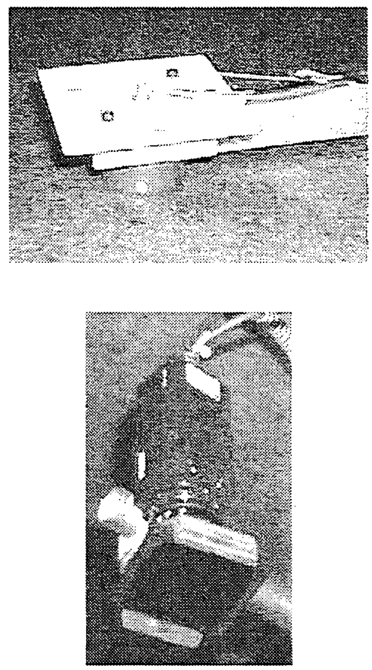

Fig 2.3. Flexible Appendage Tip with LED Targets (upper) and Optical Infrared Sensing Camera (lower)

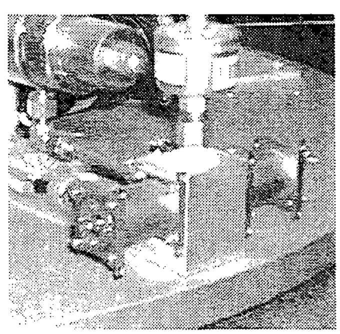

Fig 2.4. Cold Gas Jet Thrusters Mounted on Main Body

Data acquisition and control of the FSS is accomplished with a rapid design prototyping and real time control system; a dSPACE system. The dSPACE system consists of a PC host machine and a TI-C30 real time control processor. Real time code is developed on the host machine via Matlab/Simulink Real-time Workshop and is downloaded to the control processor for implementation. Analog sensor signals are accessed by the control processor through an analog-to-digital (A/D) converter. The microprocessor computes the control action according to the downloaded control law and outputs the control action in digital format. The control signal is converted to analog signals via a digital-to-analog (D/A) converter and sent to the FSS system for implementation. All A/D and D/A inputs are bipolar with a voltage range of ±10 volts. A high voltage power amplifier with a gain of 15 is used to amplify the signal sent to the piezoceramic actuator. This gain on the signal significantly enhances the structural control capabilities without running the risk of de-poling the piezoceramic actuators.

3. PWPF Modulation

The PWPF modulator produces a pulse command sequence to the thruster valves by adjusting the pulse width and pulse frequency. In its linear range, the average torque produced equals the demand torque input. Compared with other methods of modulation, PWPF modulator has several superior advantages such as close to linear operation, high accuracy and adjustable pulse-width and pulse-frequency that provide scope for advanced control.

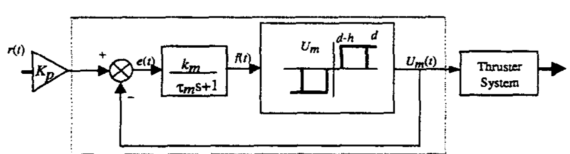

Fig.3.1 The PWPF modulator

As shown in Fig.3.1, the PWPF modulator is comprised of a Schmidt Trigger, a pre-filter, and a feedback loop. A Schmidt Trigger is simply an on-off relay with a deadzone and hysteresis. When a positive input to the Schmidt Trigger is greater than d (also denoted as E_{on}), the trigger output is U_m. Consequently, when the input falls below d-h (also denoted as E_{off}), the trigger output is 0. This response is also reflected for negative inputs. The Schmidt Trigger output, U_m, from the feedback loop, and the system input, $r(t)$, form the error signal $e(t)$. The error is fed into the pre-filter whose output $f(t)$ feeds the Schmidt Trigger. The parameters of interest are the pre-filter coefficients k_m and τ_m, input gain K_p, and the Schmidt Trigger parameters d, h, and U_m.

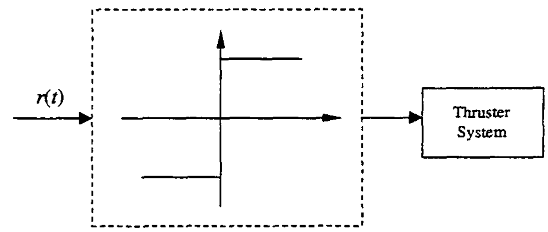

Fig.3.2 Bangbang control

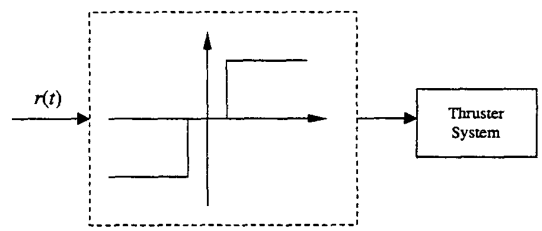

Fig.3.3 Bangbang control with deadzone

On the other hand, bangbang controller (Fig.3.2) can also be used to convert a continuous signal to an on-off type signal that is suitable for thruster control. A variation of a bangbang controller is to use a deadzone (Fig.3.3) so that the number of thruster firings and fuel consumption can be reduced at a possible cost of control accuracy. In this research, the effect of PWPF modulation will be compared with that of bangbang control and deadzoned bangbang control, respectively.

4. Smart Structures and PPF Control

A smart structure employs distributed actuators and sensors, and one or more microprocessors that analyze the responses from the sensors and use distributed-parameter control theory to command the actuators to apply localized strains to insure the system respond in a desired fashion. A 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 as damage or failure). Smart actuators are 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. Much of the early development of smart structure technology was driven by space applications such as vibration and shape control of large flexible space structures. Now smart structure research has been extended to aeronautical and other systems.

Piezoceramic material will be used in this research as a sensor to detect and as an actuator to suppress structural vibration. Piezoceramic material possesses the property of piezoelectricity, which describes the phenomenon of generating an electric charge in a material when subjected to a mechanical stress (direct effect), and conversely, generating a mechanical strain in response to an applied electric field. This property prepares piezoceramic materials to function as both sensors and actuators. The advantages of piezoceramic include high efficiency, no moving parts, fast response, and compact size. A commonly used piezoceramic is the Lead zirconate titanate (PZT), which has a strong piezo-effect. PZT can be fabricated into different shape to meet specific geometric requirements. PZT patches are often used as both sensors and actuators, which can be integrated into structures. PZT actuation strain can be on the order of 1000μstrain. Within the linear range PZT actuators produce strains that are proportional to the applied electric field/voltage. These features make them attractive for structural control applications. The FSS is equipped with 2 PZT patches as sensors bonded on the roots of both the base beam and the remote beam. One PZT patch is also bonded to the root of the base beam to function as an actuator.

For active vibration control of the flexible appendage, the positive position feedback (PPF) control scheme shown in Fig. (4.1) is well suited to implementation utilizing the piezoelectric sensors and actuators. In PPF control methods, structural position information is fed to a compensator. The output of the compensator, magnified by a gain, is fed directly back to the structure. The equations describing PPF operation are given as

$$\begin{aligned}\ddot{\xi}(t)+2\zeta_s\omega_s\dot{\xi}(t)+\omega_s^2\xi(t)&=G\omega_s^2\eta\\ \ddot{\eta}(t)+2\zeta_c\omega_c\dot{\eta}(t)+\omega_c^2\eta(t)&=\omega_c^2\xi\end{aligned} \qquad (4.1)$$

where ξ is a coordinate describing displacement of the structure, ζ_s is the damping ratio of the structure, ω_s is the natural frequency of the structure, G is a feedback gain, η is the compensator coordinate, ζ_c is the compensator damping ratio, and ω_c is the frequency of the compensator.

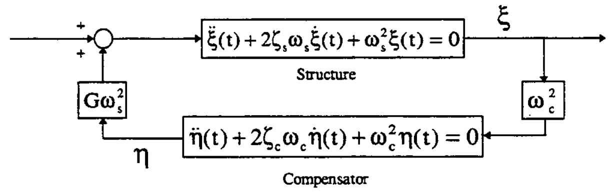

Fig. 4.1. Positive Position Feedback block diagram

The stability condition for the combined system in Eqn. (4.1) is given as

$$\frac{\varsigma_s\omega_s^3+\varsigma_c\omega_c^3+4\varsigma_s\omega_s\varsigma_c^2\omega_c^2}{(\varsigma_s\omega_s+\varsigma_c\omega_c)\omega_s\omega_c}<G<1$$

For more interpretation of the PPF compensator, we introduce a frequency domain analysis. Assume ξ is given as

$$\xi(t)=X e^{i\omega_s t}$$

then the output of the compensator is

$$\eta(t)=\frac{X\,\omega_s/\omega_c\, e^{i(\omega_s t-\phi)}}{\sqrt{\left(1-\omega_s^2/\omega_c^2\right)^2+\left(2\varsigma_c\,\omega_s/\omega_c\right)^2}}$$

where the phase angle ϕ is

$$\phi=\tan^{-1}\left[\frac{2\varsigma_c\,\omega_s/\omega_c}{1-\omega_s^2/\omega_c^2}\right]$$

Therefore

$$\frac{\eta}{\xi}=\frac{e^{-i\phi}}{\sqrt{\left(1-\omega_s^2/\omega_c^2\right)^2+\left(2\varsigma_c\,\omega_s/\omega_c\right)^2}} \qquad (4.2)$$

The system frequency response characteristics are shown in Fig. (4.2). It is seen in the figure, when the PPF compensator's frequency is in the region of the structure's natural frequency, the structure experiences active damping. Additionally, when ω_c is lower than ω_s, active flexibility results and when ω_c is larger than ω_s, active stiffness results. Clearly, to maximize damping in the structure, the compensator's frequency should be closely matched to ω_s. Analytical and experimental study of active vibration control of a flexible beam using PPF compensator by Song et al (1998) reveal that PPF compensator with a relative high damping ration is robust to variations in modal frequencies. This is another reason why PPF is adopted in this research.

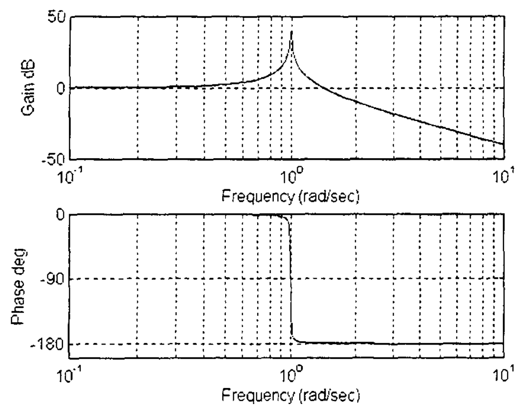

Fig. 4.2 Frequency response of system to PPF controller ω_s=1 rad/sec, ζ_s=0.005, G=1.

5. Vibration Reduction for FSS Attitude Control using PWPF Modulator and PPF Control

The control system for vibration reduction of the FSS during attitude maneuvers consists of two sub-systems, the attitude control sub-system using PWPF modulation and the active vibration suppression sub-system using smart structures, as shown in Fig. 5-1. The attitude feedback control sub-system employs a proportional plus derivative (PD) controller and the active vibration suppression sub-system uses positive position feedback control strategy. The attitude control sub-system provides a means for passive vibration control by using PWPF modulation to reduce vibrations introduced to FSS due to thruster firing. The active vibration suppression uses the PZT sensor and actuator to actively cancel the thruster-firing-induced vibration on the flexible appendage. These two sub-systems work together to reduce vibrations during attitude maneuver operations, such as slew and station keeping.

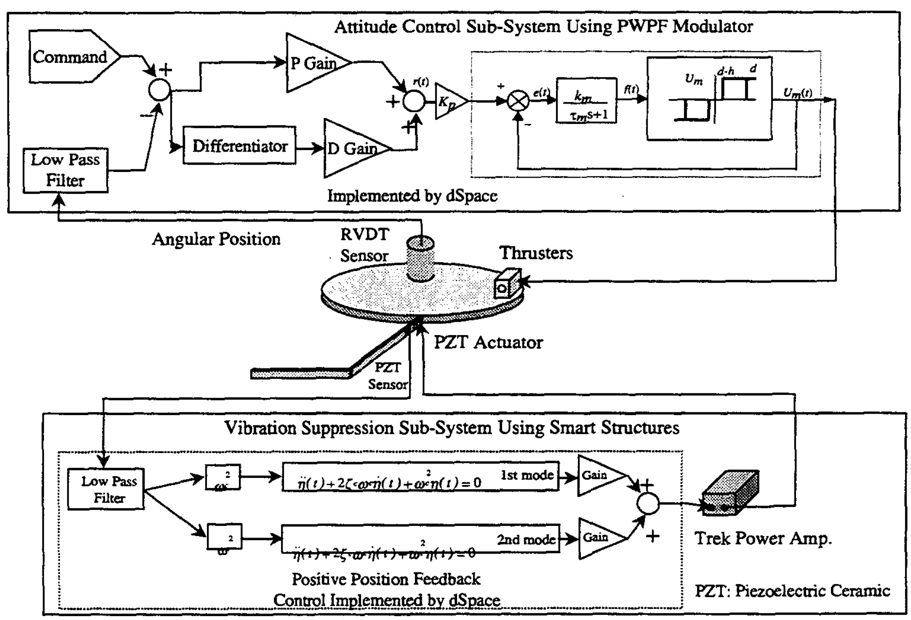

Fig. 5-1 The block diagram illustrating the control system for FSS vibration reduction

In the attitude control sub-system, the RVDT sensor detects the angular displacement of the FSS rigid body and then, via an analog to digital converter, the signal is sent to the dSPACE system, where the signal is digitally processed by a low-pass filter and a differentiator. The processed signal is then used to produce a proportional plus derivative (PD) control action. Before being sent to the digital to analog converter, the PD control signal is converted to on-off signals by a digital PWPF modulator. Finally the on-off signals are sent to the thrusters to implement the control action and to reorient the FSS.

In the active vibration suppression sub-system, the PZT sensor bonded at the root of the base beam of flexible appendage detects the vibration of the appendage and the signal is then sent to the DSP via an analog to digital converter. After a low-pass filter, the signal is used by two positive position controllers, targeting at the first two modes of the FSS system modes, to produce control signal. After the digital to analog converter, the control signal is amplified via a Trek voltage amplifier and then fed to the PZT actuator to actively suppress vibrations of the flexible appendage.

During the experiment, the vision server system is used to record the global position of the tip, elbow, and base of the flexible appendage.

6. Experimental Results

6.1 Slew Maneuver

In this experiment, the FSS is commanded to perform a 30-degree slew. For comparative purposes, four different cases of a 30-slew of the FSS are conducted. 1) Slew using PWPF modulation and active vibration suppression. 2) Slew using bangbang control (no deadzone) and active vibration suppression. 3) Slew using deadzoned-bangbang control and active vibration suppression. 4) Slew using PWPF modulation but without active vibration suppression. Case 1 is compared against cases 2 and 3 to demonstrate the advantages of PWPF modulation for attitude control over bangbang control with or without deadzone. On the other hand, case 1 is compared with case 4 to show the effectiveness of active vibration suppression of thruster-firing-induced vibration using smart structures during attitude control. The proportional gain and the derivative gain of the PD controller for attitude control are 10 and 100, respectively. The PWPF modulator parameters are given in Table 6-1-1, and PPF controller parameters are given in Table 6-1-2.

Table 6-1-1 PWPF Modulator Parameters

Parameter	Value
K_m	1.25
U_m	2.0
τ_m	0.5
E_{on} (d)	0.45
E_{off} $(d\text{-}h)$	0.20

Table 6-1-2 PPF Controller Parameters

Parameter	1st Mode	2nd Mode
Targetted Frequency (ω_c)	.3 Hz	.9 Hz
Gain	5	5
Damping Ration (ζ_c)	.15	0.20

First, the PWPF modulator is employed in the attitude control subsystem to slew the FSS for 30-degree with active vibration suppression using PZT actuator and sensors. The angular displacement of the rigid body along with vibrations of both base beam and remote beam are shown in Fig. 6-1-1. The angular displacement signal of the rigid body is obtained from the RVDT sensor. The vibration signals for both the base beam and the remote beam are obtained from the PZT patch sensors bonded to the root of the two beams. Then, the same experiment is repeated with a bangbang controller replacing the PWPF modulator and the experimental results are shown in Fig. 6-1-2. It is clear that, from comparison of Figs. 6-1-1 and 6-1-2, the thruster firing under PWPF modulator introduces much less vibration to both the rigid body and the flexible appendage than the bangbang control does. Also excessive thruster firing is observed for the bangbang control. A comparison of the power spectrum density (PSD) plots for these two cases is shown in Fig. 6-1-

3. The remote sensor data are used for the PSD plots. With the PWPF modulation, the energy levels for the first three modes are about 18dB, 30 dB, and 15dB less than those with bangbang control. Using the overhead vision server camera, the tip, elbow and base positions of the flexible appendage are recorded. Figs 6-1-4 and 6-1-5 show these results for two 30-degreee slewes with PWPF modulation and bangbang control, respectively. The trace of the tip position in Fig 6-1-4 is smoother and less oscillatory as compared with that in Fig.6-1-5. This reflects the advantages of PWPF modulation over bangbang control.

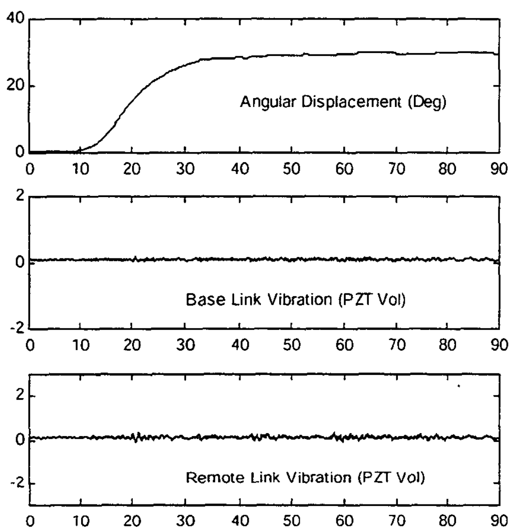

Fig. 6-1-1 Slew with PWPF Modulation and Active Vibration Suppression

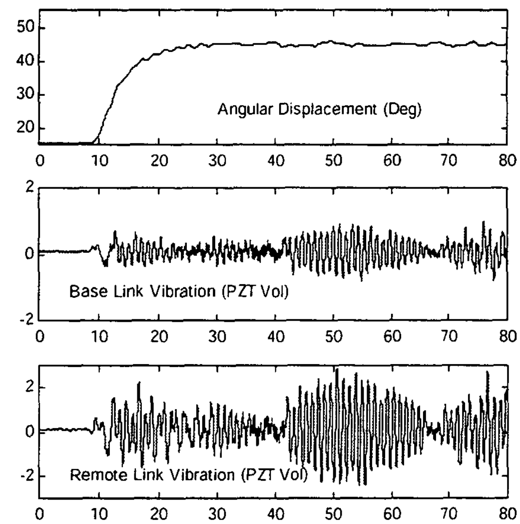

Fig. 6-1-2 Slew with Bangbang Control (No deadzone) and Active Vibration Suppression

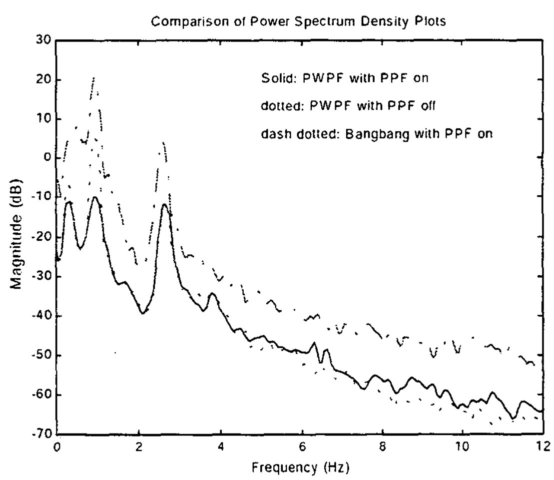

Fig. 6-1-3 Comparison of Power Spectrum Density Plots

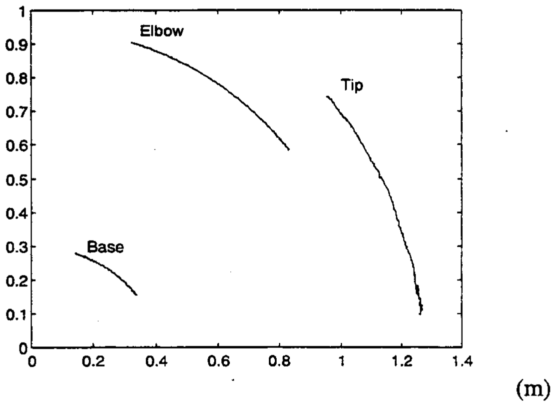

Fig. 6-1-4 Trace of the Flexible Appendage Movement during a 30-deg Slew with PWPF Modulation and Active Vibration Suppression

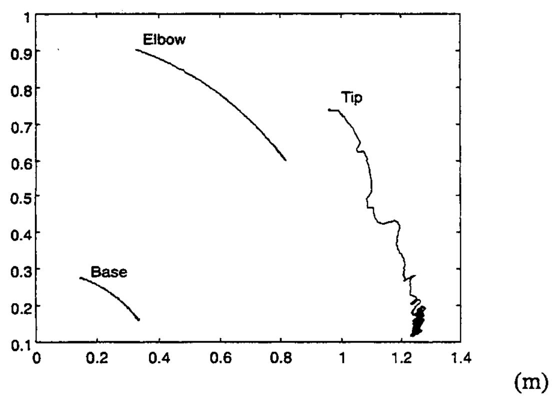

Fig. 6-1-5 Trace of the Flexible Appendage Movement during a 30-deg Slew with Bangbang Control (no deadzone) and Active Vibration Suppression

To reduce the thruster firing when bangbang control is used, the case of bangbang controller employs a deadzone is also tested. The deadzone is set from -0.45 to +0.45, which corresponds to the data for the PWPF modulator. The active vibration suppression sub-system is implemented in this case. Severe rigid body and flexible appendage interaction is observed. The vibrations of rigid body and the flexible appendage are reflected in Fig. 6-1-6. Even with a deadzone, the bangbang control still uses more fuel and more number of firings than PWPF modulated thruster control, as shown in Fig. 6-1-7. This further demonstrates the superiority of attitude control using PWPF modulation over bangbang control with or without a deadzone.

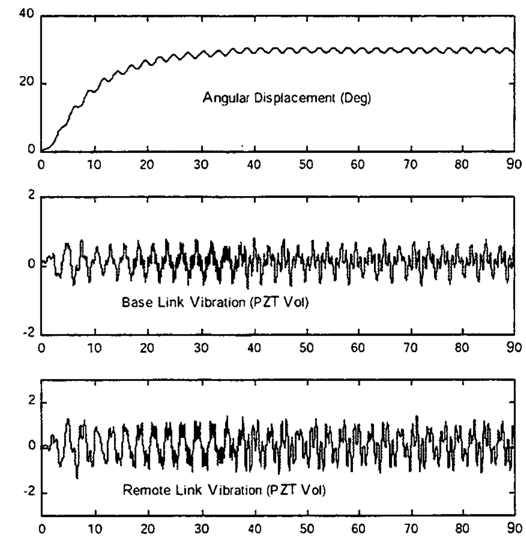

Fig. 6-1-6 Slew with Bangbang Control (with deadzone) and Active Vibration Suppression

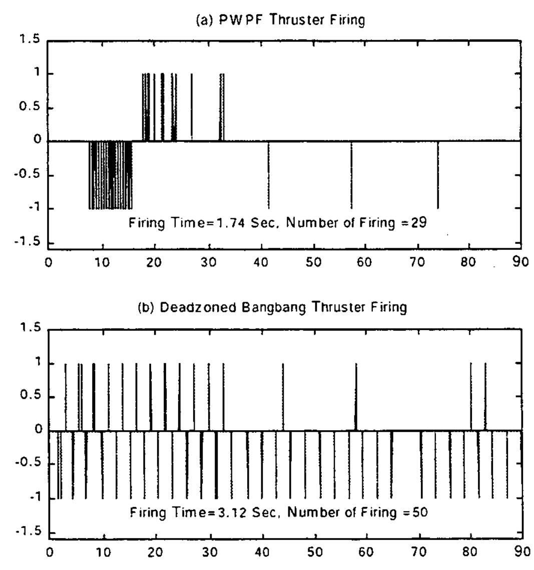

Fig. 6-1-7 Thruster Firing Comparison between (a) PWPF Modulation and (b) Deadzoned Bangbang Control

To demonstrate the effect of the active vibration suppression using smart structures, a 30-degree slew of the FSS using PWPF modulator with active vibration suppression sub-system turned off is conducted. As compared with Fig 6-1-1 when active vibration suppression sub-system is on, the vibrations observed in Fig.6-1-8 are more severe. This observation is quantified from the PSD plots in Fig. 6-1-3. Since the PPF control only targets at the 1st and 2nd modes, it is reasonable to see that the 3rd mode vibrates at the same energy level in either case. With the PPF control turned on, the 2nd mode energy level is brought down by 15 dB, while the 1st mode's is decreased by 4 dB. This shows the effectiveness of the smart structure along with PPF control for active vibration suppression.

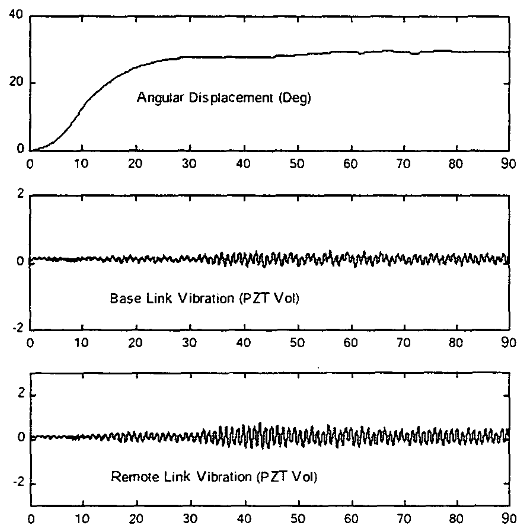

Fig. 6-1-8 Slew with PWPF Modulation but without Active Vibration Suppression

6.2 Station Keeping

In this experiment, FSS station keeping tasks are performed. To demonstrate the advantages of the PWPF modulator over the bangbang control, attitude controls using both methods are conducted. In both cases, the same active vibration suppression subsystem is used to counter react to the thruster-firing induced vibrations on flexible appendage. The PD controller employs the same gains during both tests for a fair comparison.

First, the FSS under attitude control via PWPF modulation is tested. At t=10 second, a disturbance is introduced to the FSS so the rigid body deviated about 7 degrees from its desired position, 29.5 degrees, as shown in Fig.6-2-1. In about 15 seconds, the orientation of FSS rigid body converges to around 29.5 degrees with little overshot. At the steady state, 0.5 degree error in orientation is observed. Little vibrations on the flexible appendage are observed, as indicated by the voltage outputs of PZT sensors located at both the base and remote beams. These voltage outputs are also shown in Fig. 6-2-1.

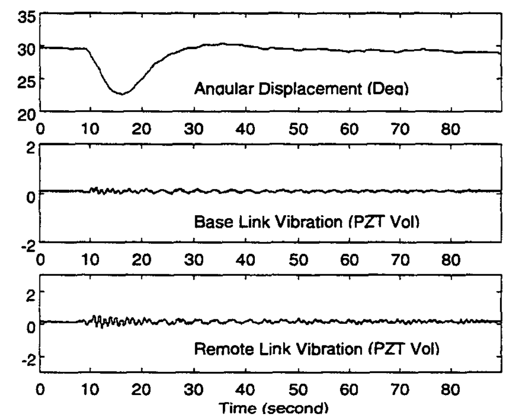

Fig. 6-2-1 Station Keeping using PWPF modulator

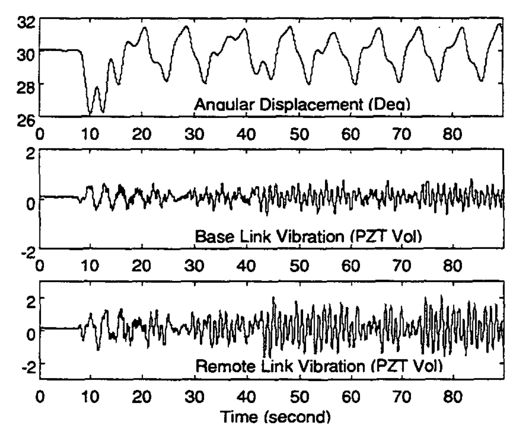

Fig. 6-2-2 Station Keeping using Bangbang Control

On the other side, when the bangbang control is used in the attitude control sub-systems, the FSS system experiences instability after a disturbance is introduced to it, as shown in Fig. 6-2-2. Violent vibrations on the flexible appendage are also observed, as confirmed by the PZT sensors voltage outputs shown in the Fig.6-2-2. Comparison of the two experiments clearly demonstrates the superiority of PWPF modulation over bangbang control during station keeping tasks.

7. Conclusions

This paper proposes a new approach to vibration reduction of flexible spacecraft during attitude maneuver. In this approach, the PWPF modulation is used to control thruster firing in the attitude control system to reduce vibrations introduced to the flexible structure, meanwhile, on the other hand, smart structures are employed to actively suppress vibrations induced by thruster firing. Experimental results of attitude control of the US Naval Postgraduate School's Flexible Spacecraft Simulator (FSS) using this approach demonstrate that the use of the PWPF modulator reduces vibration, improves pointing accuracy, and reduces fuel consumption as compared to bangbang control with or without a deadzone. Experiments also demonstrate smart structures with positive position feedback (PPF) provides actively damping to the flexible structure and helps to increase point accuracy and reduce fuel consumption. Overall, the method of vibration reduction of flexible spacecraft during attitude control using PWPF modulator and smart structures is demonstrated effective.

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References:

Agrawal, B.N. and Bang, H., "Adaptive Structure for Large Precision Antennas," 45th Congress of the International Astronautical Federation (Jerusalem, Israel), October, 1994.

Anthony, T., Wei, B., and Carroll, "Pulse-Modulated Control Synthesis for a Flexible Spacecraft," AIAA J. of Guidance, Control, and Dynamics, Vol. 13, No. 6, November-December, 1990, pp. 1014-1015.

Bittner, H., Fischer, H.D., and Surauer, M. "Design of Reaction Jet Attitude Control Systems for Flexible Spacecraft," IFAC Automatic Control in Space (Noordwijkerhout, The Netherlands), 1982.

Clark, R.N. and Franklin, G.F., "Limit Cycle Oscillations in Pulse Modulated Systems," J. of Spacecraft and Rockets, Vol. 6, No.7, July 1969, pp. 799-804.

Fanson, J.L. and Caughey, T.K., "Positive Position Feedback Control for Large Space Structure," AIAA Journal, Vol. 28, No. 4, April, 1990, pp.717-724.

Goh, C.J. and Caughey, T.K., "On the Stability Problem Caused by Finite Actuator Dynamics in the Collocated Control of Large Space Structure," Int. J. Control, Vol. 41, No. 3, 1985, pp.787-802.

Hablani, H.B., "Multiaxis Tracking and Attitude Control of Flexible Spacecraft with Reaction Jets," AIAA J. of Guidance, Control, and Dynamics, Vol. 17, No. 4, July-August, 1994, pp. 831-839.

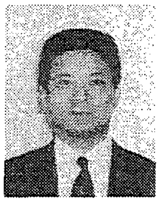
Millar, A. and Vigneron, F.R., "Attitude Stability of Flexible Spacecraft Which Use Dual Time Constant Feedback Lag Network Pseudorate Control," AIAA/CASI 6th Communications Satellite Systems Conference (Montreal, Canada), April, 1976.

Song, G., Buck, N., and Agrawal, B, "Spacecraft Vibration Reduction Using Pulse-Width Pulse-Frequency Modulated Input Shaper", to appear in AIAA Journal of Guidance, Control, and Dynamics, 1998a.

Song, G., S. Schmidt, and B.N. Agrawal, "Experimental Study of Vibration Suppression of Flexible Structure Using Modular Control Patch", Proceedings of IEEE Aerospace Conference (Snowmass, Co), 1998b.

Wie, B., and Plescia, C.T., "Attitude Stabilization of Flexible Spacecraft During Station keeping Maneuvers," J. of Guidance, Control, and Dynamics, Vol. 7, No. 4, 1984, pp. 430-436.

Biography



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