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Adaptive Robust Vibration Control with Input Shaping as a Flexible Maneuver Strategy

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An adaptive robust control is presented for the vibration reduction of a flexible spacecraft by combining the input shaping technique with the sliding-mode control. The combined approach appears to be robust in the presence of a severe disturbance and an unknown parameter which will be estimated by on-line least-square method. As a maneuver strategy, it is found that a synthesized trajectory with a combination of low-frequency mode and rigid-body mode results in better performance and is more efficient than the traditional rigid-body trajectory alone which many researchers have employed. The feasibility of the vibration control approach is demonstrated by applying it to a benchmark problem in aerospace. For the applications of the proposed technique to realistic flexible spacecraft systems, several requirements are discussed such as mode stabilization and enormously large system order.

Key Words : Sliding-Mode Control, Input-Shaping Control, Vibration Reduction, Parameter Estimation, Tracking Model

1. Introduction

Numerous papers have been written about controlling flexible spacecrafts. There have been many approaches in control methodology such as H_∞ control (Wei and Byun, 1992), adaptive control (Tzes, 1990), optimal control (Meirovitch and Quinn, 1987; Kim and Park, 1991), and so on. However, they are mainly focused on a maneuver based on a rigid-body-like operation without allowing flexibility on the system. Since the 1980s, control systems have become more sophisticated due to the consideration of flexibility in addition to rigid-body dynamics. Of course, it is possible for a flexible spacecraft to adopt the rigid-body maneuver concept of satellite systems in 1970s. As a result, many of the resulting systems have suffered from vibration even if the control objective is intended to be vibrationless for the flexible structure during operations. This is a motivation to present an alternative approach to reduce vibration in spacecraft maneuvers.

Sung and Wander (1994) evaluated the input shaping technique of Singer and Seering (1990) with a linear system model. The performance was remarkable in the rotational maneuver. However, real systems will be exposed to non-ideal effects such unmodeled dynamics, parameter uncertainties, disturbances, high dimensionality, etc. In their evaluation, the input shaping technique cannot handle the non-ideal effects.

Therefore, an adaptive robust control approach is presented by combining the input shaping technique with sliding-mode control to reduce the residual vibration. The main idea is the reduction of vibration and control energy consumption while allowing vibration in the system during the operation, especially in the application of a point-to-point maneuver which requires the control of system attitude and flexible structure vibration. In other words, the system vibration of flexible structure is utilized rather than eliminated during the operation. The adaptive incorporation of both controllers and the utilization of system vibration are different from other methods.

The organization of the paper is as follows. In

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the next section, the adaptive robust controller is developed with a benchmark model by including parameter estimation. Then, the input shaping technique is briefly discussed for the utilization of flexible maneuver strategy so that the system will experience natural vibration during maneuvers. Following this are numerical results for in restigating the non-ideal effects and the conclusion.

2. Adaptive Robust Vibration Control for Benchmark Problem

In order to develop an adaptive robust vibration controller, a simple generic model known as a benchmark problem in aerospace is shown in Fig. 1 and is utilized to illustrate the control concept and methodology. Lastly, the control concept is presented.

The equations of motion of two-mass-spring-damper system shown in Fig. 1 are

$$m_1\ddot{x}_1+D(\dot{\tilde{x}},\tilde{x})\dot{\tilde{x}}+k\tilde{x}=u+w \tag{1}$$

$$m_2\ddot{x}_2+D(\dot{\tilde{x}},\tilde{x})\dot{\tilde{x}}+k\tilde{x}=0 \tag{2}$$

where $\tilde{x}=x_1-x_2$. x_1 and x_2 are the displacements of mass m_1 and mass m_2, respectively. By defining the state variables as $x=[x_1\ x_2\ \dot{x}_1\ \dot{x}_2]^T$, this system can also be represented in state space form as

$$\dot{\mathrm{x}}=\mathrm{A}\mathrm{x}+\mathrm{B}(u+w) \tag{3}$$

$$\mathrm{A}=\begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ -k/m_1 & k/m_1 & -D(\dot{\tilde{x}},\tilde{x})/m_1 & D(\dot{\tilde{x}},\tilde{x})/m_1\\ k/m_2 & -k/m_2 & D(\dot{\tilde{x}},\tilde{x})/m_2 & -D(\dot{\tilde{x}},\tilde{x})/m_2\end{bmatrix}$$

$$\mathrm{B}=\begin{bmatrix}0\\0\\1/m_1\\0\end{bmatrix}$$

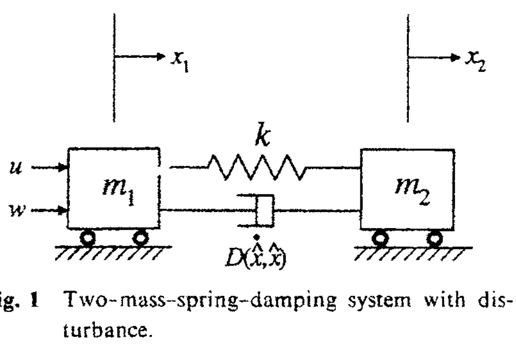

Fig. 1 Two-mass-spring-damping system with disturbance.

where u and w are the control input and the external disturbance, respectively. In the state equation, the nonlinear damping is presented due to the increment of size and flexibility of space structures increases the need to characterize the energy dissipation in a more appropriate and accurate manner. Numerous experimental results, such as those in the Spacecraft Control Laboratory Experiment (SCOLE) (Taylor, 1987), indicate that proportional damping assumptions are not sufficient and that there is a great need for understanding the damping mechanism that may be inherently nonlinear.

Various nonlinear models, such as linear dampers with clearance, coulomb friction dampers, velocity-nth power damping, and so forth, have been investigated. In many cases, these models can be represented by a damping force that is proportional to the product of the integer or fractional powers of the absolute values of displacement and velocity. The following damping model (Taylor, 1987) is representative of a variety of nonlinear damping mechanisms

$$D(\dot{\tilde{x}},\tilde{x})=c|\dot{\tilde{x}}|^a|\tilde{x}|^b \tag{4}$$

where c is a constant, and a, $b>0$.

2.1 Design of sliding-mode controller

The coupled single-input system in Fig. 1 is written as

$$\ddot{x}_1=\frac{1}{m_1}[-D(\dot{\tilde{x}},\tilde{x})\dot{\tilde{x}}-k\tilde{x}+u+w] \tag{5}$$

$$\ddot{x}_2=\frac{1}{m_2}[D(\dot{\tilde{x}},\tilde{x})\dot{\tilde{x}}+k\tilde{x}] \tag{6}$$

where the true nonlinear damping term $D(\dot{\tilde{x}},\tilde{x})\dot{\tilde{x}}$ is estimated as $\hat{c}\dot{\tilde{x}}$ where $\hat{c}$ is a constant with

$$|-D(\dot{\tilde{x}},\tilde{x})\dot{\tilde{x}}+\hat{c}\dot{\tilde{x}}|\le\left(1\frac{N\cdot\sec}{m}\right)|\dot{\tilde{x}}|=F \tag{7}$$

The sliding plane is defined as, namely,

$$s_1(x,t)=0\quad \textit{with}\quad s_1=\dot{\tilde{x}}+\lambda\tilde{x}_1 \tag{8}$$

where $\tilde{x}_1=x_1-x_{d1}$ is a tracking error. To satisfy a sliding condition, a control law u is designed as

$$u=k\tilde{x}+\hat{c}\dot{\tilde{x}}+m_1(\ddot{x}_{d1}-\lambda\dot{\tilde{x}}_1)-K\,sgn(s_1) \tag{9}$$

where $sgn(s_1)=-1$ for $s_1<0$ and $sgn(s_1)=+1$ for $s_1>0$ and $K=\eta+F$ and a strictly positive constant η. Of course, we might have a chattering

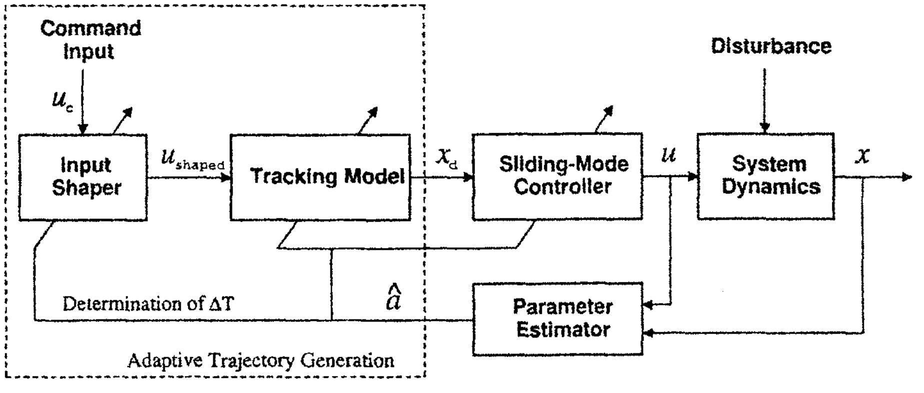

Fig. 2 Adaptive robust vibration control diagram.

problem so that the concept of boundary layer with saturation function (Slotine and Li, 1991) could be employed. Several techniques are found in Mostafa and Öz (1989) for more advanced chattering reduction.

2.2 Input shaping technique

The input shaping technique was developed by Singer and Seering (1990) to reduce the residual vibration of a linear second-order damped system in terms of impulse sequence. More detailed descriptions can be found in reference (Singer and Seering, 1990). Here, the result of a two-impulse sequence for one vibrational mode is presented in order to shape an input command. By selecting $t_1=0$ for the time of the first impulse, and $A_1=1$ for the amplitude, the simple solution can be obtained

$$A_2=e^{-\zeta\omega\Delta T} \tag{10}$$

where

$$\Delta T=\frac{\pi}{\sqrt{\omega 1-\zeta^2}} \tag{11}$$

where ω is a natural frequency. The input shaping technique can also be used to deal with higher modes. For instance, if a two-impulse sequence is designed for each of the two modes of a closed-loop system, respectively, they can be convolved to form a sequence which moves this two-mode system without residual vibration (see (Ref. Singer and Seering, 1990) for more detailed descriptions). In order to generate an input for the vibrationless motion, any arbitrary desired input to the system can be obtained by convolving with the impulse sequence.

2.3 Tracking model

A tracking model is used in order to allow the natural vibration of a system. The tracking model can be obtained from Eq. (3) by excluding non-ideal terms. In other words, the tracking model provides ideal states to the sliding-mode controller so that it serves as nominal linear trajectory. The tracking model is expressed as the state equation

$$\dot{x}_d=A_m x_d+B_m u_{shaped} \tag{12}$$

With the tracking model, the desired state trajectory can be generated and supplied to the sliding-mode controller. In the numerical simulation, the stiffness is included only for the generation of flexible state trajectory.

2.4 Parameter estimation

For the investigation of the combined control approach (input shaping technique and sliding-mode control), a parameter estimation is implemented to see how well the approach works and what the effect of a time-varying parameter to the combined approach is during the parameter estimation process. Parameter estimation based on least-square of errors with exponential forgetting (Slotine and Li, 1991) is employed to deal with time-varying parameters in a real time process. If exponential forgetting of data is incorporated into least-square estimation, one minimizes

$$J=\int_0^t e^{-\int_s^t \mu(r)dr}|y(s)-W(s)\hat{a}(t)|^2 ds \quad (13)$$

where vector $y(s)$ contains the outputs of the system, the vector $\hat{a}$ is unknown parameters, $W(s)$ is a signal matrix, and $\mu(t)\geq 0$ is a time-varying forgetting factor. The update law is

$$\dot{\hat{a}}=-P(t)W^T e_1 \quad (14)$$

where $e_1=\hat{y}(t)-y(t)$ and $\hat{y}(t)=\hat{a}W^T(t)$ is the predicted output at time t. For simplicity, the nonlinear damping term is assumed to be known in constant stiffness estimation so that the effect of unknown stiffness can be evaluated with respect to the flexible maneuver trajectory. For the benchmark problem with unknown scalar stiffness $\hat{a}=k$, the output $y(t)$ which contains the parameter information from Eq. (2) can be written as

$$y(t)=m_1\ddot{x}_1-m_2\ddot{x}_2+2c|\dot{x}_1-\dot{x}_2|^a|x_1-x_2|^b(\dot{x}_1-\dot{x}_2)-u \quad (15)$$

and

$$W^T(t)=-2(x_1-x_2). \quad (16)$$

The scalar gain updates as

$$\dot{P}(t)=-\mu(t)P(t)-P(t)W^T(t)W(t)P(t). \quad (17)$$

In this implementation, the forgetting factor is given as

$$\mu(t)=\mu_0\left(1-\frac{|P(t)|}{k_0}\right) \quad (18)$$

where μ_0 and k_0 are positive constants.

3. Numerical Simulation and Discussion

In the simulation, $u_c(t)=2\sin^2\Omega t$ is a command input chosen to simulate the point-to-point maneuver where $\Omega=1$ rad/sec. The parameter values for nonlinear damping of Eq. (4) are $a=2$, $b=1$ and $c=0.05$. It is taken that $m_1=m_2=1$ and $k=1$ with appropriate units and time is in units of seconds. The control force $u(t)$ acts on mass m_1. An external disturbance (Wei and Byunm, 1992) $w(t)=\sin 0.5t$ is acting on mass m_1. Especially, the sinusoidal disturbance (Chun et. al., 1985) can be caused by crew motions and instrument operations on board. In the sliding-mode controller, the strictly positive constant η is 0.05. With the model in Fig. 1, three different control combinations are conducted with respect to nonlinear damping, sinusoidal disturbance and an unknown parameter.

First, the input shaping technique showed excellent performance in the ideal case (Sung and Wander, 1993). In the paper, the performance of the input shaping technique is tested with respect to nonlinear damping and external disturbance.

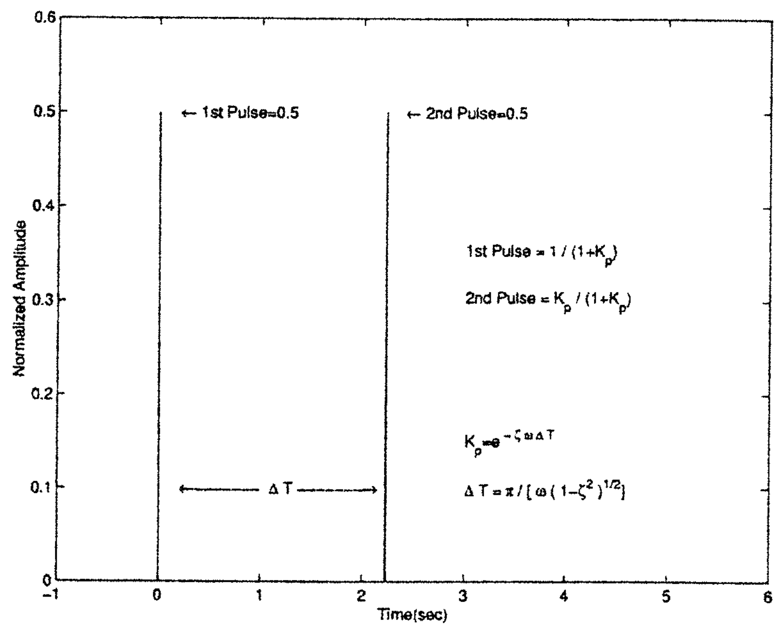

Fig. 3 Pulse sequence for flexible spacecraft.

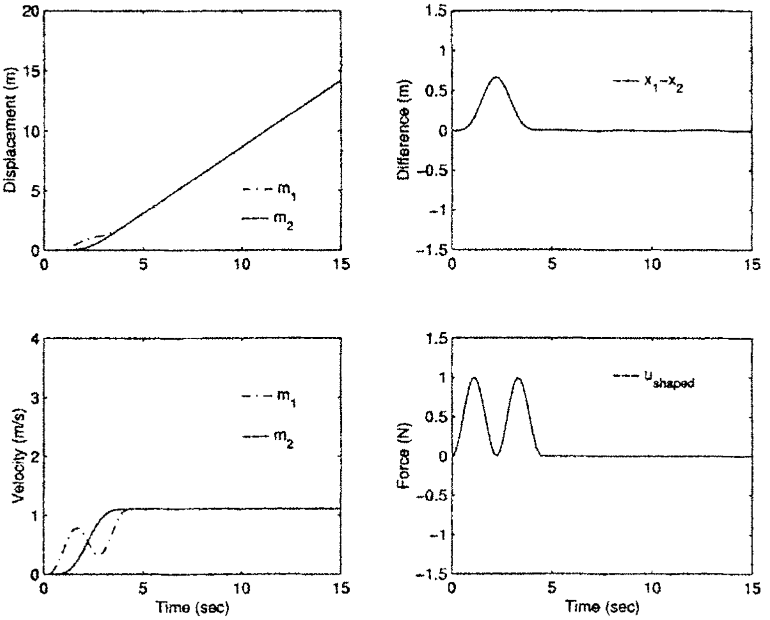

Fig. 4 Simulation with nonlinear damping using input shaping technique.

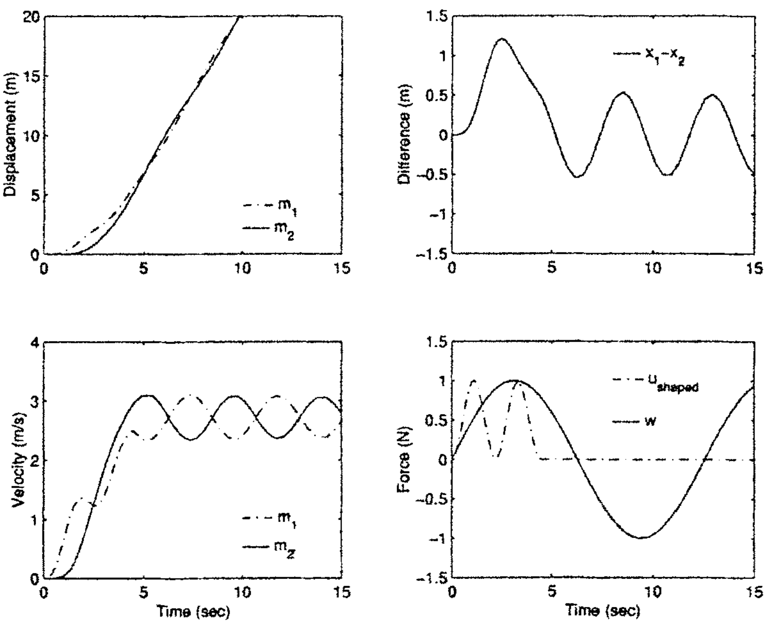

Fig. 5 Simulation with nonlinear damping and disturbance using input shaping technique.

The two-impulse sequence is shown in Fig. 3. In Fig. 4, the simulation shows that the input shaping technique cannot treat the nonlinear damping effect perfectly, unlike the linear problem. Of course, the inclusion of more pulses can provide a certain degree of robustness. There is some residual vibration after the end of the operation. In Fig. 5, the sinusoidal disturbance is included in the system. It shows that the input shaping technique can not handle the disturbance with large oscillation in both bodies because the sinusoidal disturbance is added to the shaped input. In the

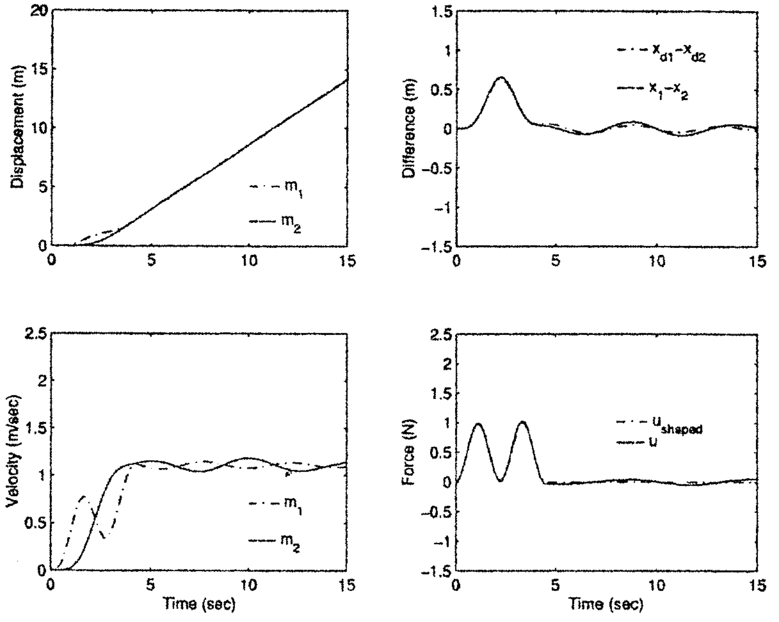

Fig. 6 Simulation with nonlinear damping using input shaping technique and sliding-mode control.

previous two simulations, the performance of the input shaping technique is investigated with respect to non-ideal effects. It implies that the input shaping technique alone cannot be used for non-ideal problems since it has the nature of an open-loop control.

Second, in order to treat non-ideal effects such as unmodeled dynamics, system uncertainties, and others, it is typical to employ a feedback control technique. Hence, the sliding-mode controller without a parameter adaptation is employed to increase robustness and performance by incorporating with the input shaping technique. The combined approach is different from popular methods in the sense of tracking the linear states as an operational strategy so that the controlled system will experience a half period of natural vibration.

In Fig. 6, the combination of the input shaping command with the sliding-mode controller without a parameter adaptation in Eq. (9) is applied to the same case of Fig. 4. In this simulation, the sliding-mode controller is operating all the time after the transient motion so that both masses are vibrating lightly, because the linear tracking model with the nonlinear damping factor is used. In order to eliminate an adverse effect, it is necessary that the sliding-mode controller tracks set-point states after the desired maneuver. However, it is shown that mass m_1 is tracking the expected path. The control input $u(t)$ is similar to the shaped input u_{shaped} because the nonlinear damping effect is small. Therefore, the dynamics of the given model is closely following the designed tracking path during the maneuver. In the case of employing the sliding-mode controller alone, the simulation in Fig. 7 with rigid-body tracking states shows that mass m_1 has arrived to the desired states but mass m_2 appears to be vibrating with large amplitude. From the case, we can conclude that the combination of the controllers results in better performance.

The external disturbance is included to see how the proposed approach works in Fig. 8. The sinusoidal disturbance is precisely controlled by the sliding-mode controller unlike the case the input shaping technique is applied alone as shown in Fig. 5. After the transient move, the proposed control mechanism is properly counteracting the disturbance.

A 20% parameter error in stiffness is assigned in the absence of the sinusoidal disturbance in order to see the effect of modeling error in Fig. 9. It

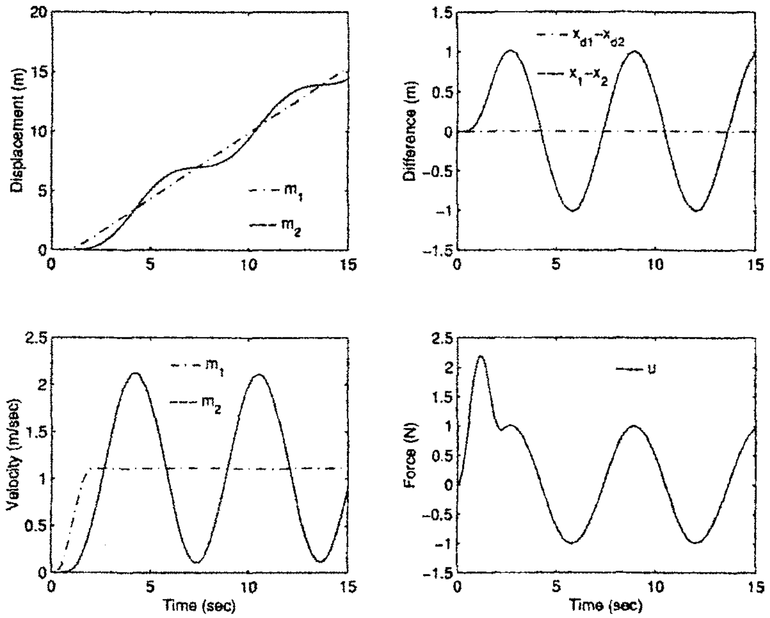

Fig. 7 Simulation with nonlinear damping only using sliding-mode control.

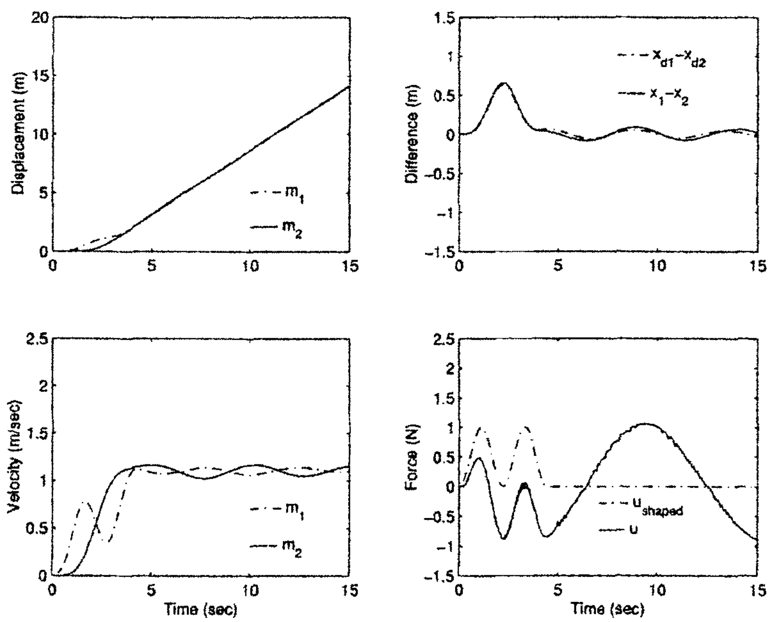

Fig. 8 Simulation with nonlinear damping and disturbance using input shaping technique and sliding-mode control.

shows that masses m_1 and m_2 oscillate. It seems that the combined approach requires a reasonably accurate system model.

Third, a parameter estimator is implemented in order to cope with modeling error. All of the states are assumed to be available in the conceptual simulation. During on-line operation, a parameter in the input shaping technique, tracking model and sliding-mode control is updated. Two impulses with the same pulse amplitude are

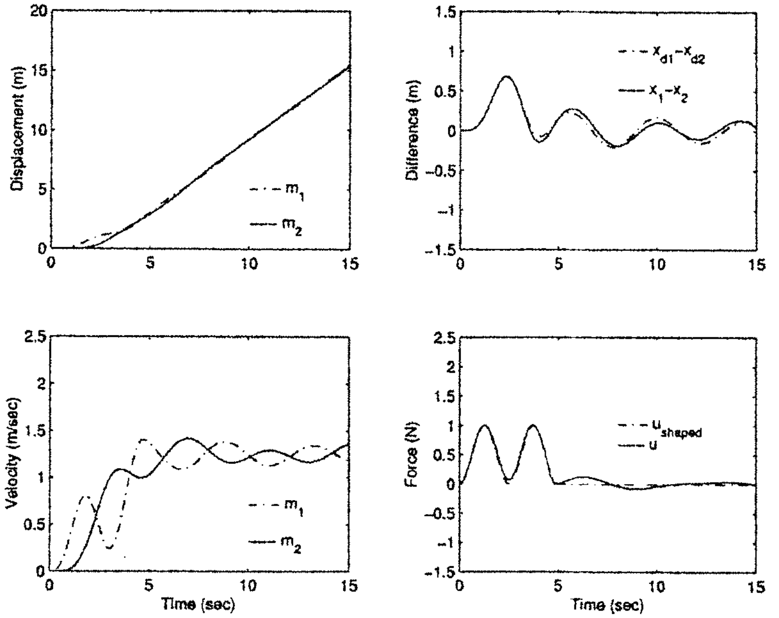

Fig. 9 Simulation with nonlinear damping and 20% modeling error in stiffness using input shaping technique and sliding-mode control.

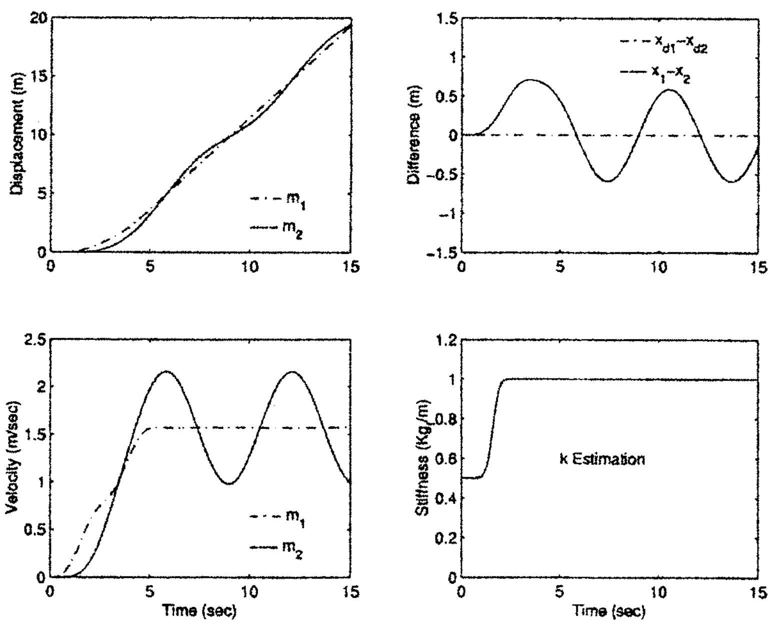

Fig. 10 Rigid-body path: input shaping technique, sliding-mode control, and estimation with nonlinear damping and 50% error in stiffness.

used for the input shaping technique because of the need of real-time application (Tzes, 1990). With a 50% error in the initial stiffness estimate, three cases with rigid, flexible and combination trajectories are compared.

A rigid-body trajectory based on the kinetics of two bodies is used in Fig. 10. The results are more desirable than those of Fig. 8 because mass m_1

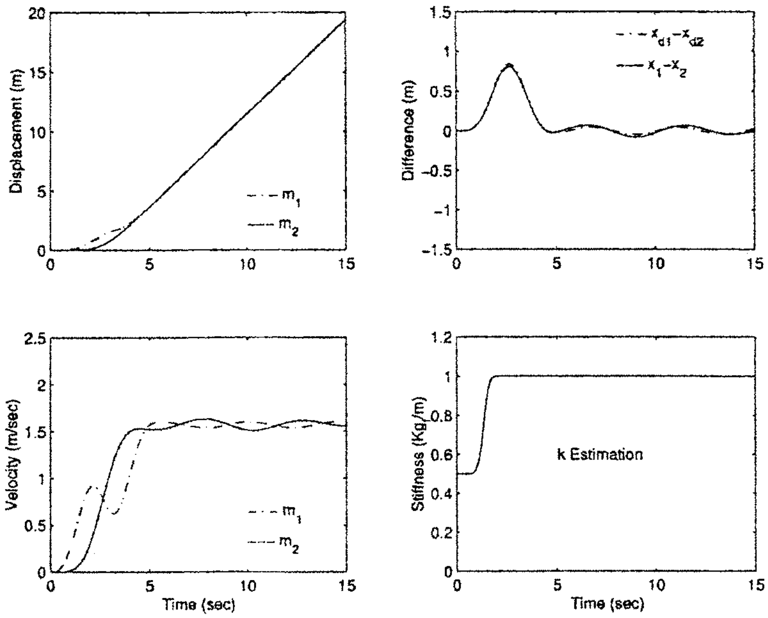

Fig. 11 Flexible path: input shaping technique, sliding-mode control, and estimation with nonlinear damping and 50% error in stiffness.

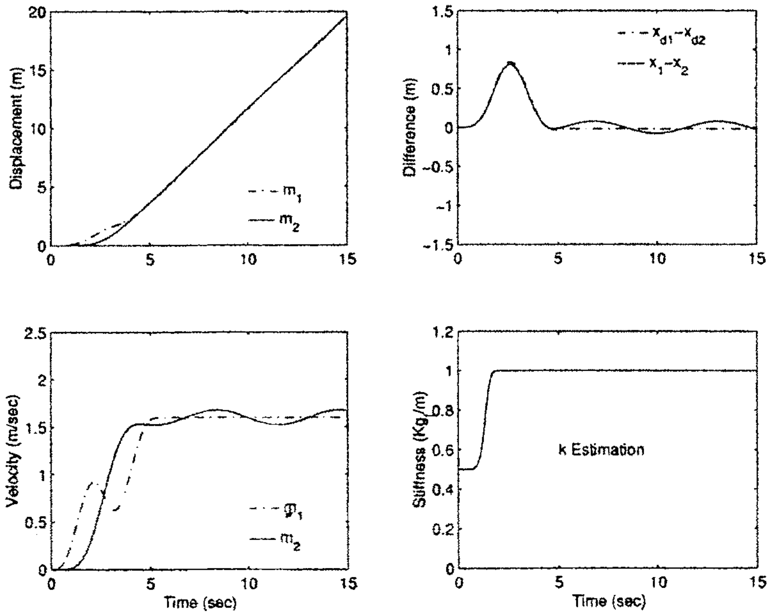

Fig. 12 Combination path: input shaping technique, sliding-mode control, and estimation with nonlinear damping and 50% error in stiffness.

tracks the desired path. On the other hand, mass m_2 has a large overshoot and the residual vibration. It seems that a rigid-body path is not appropriate in the control of the flexible structure.

A flexible-body trajectory based on the frequency of the system is implemented in Fig. 11. It shows that the results are much better than those of the rigid-body path with a small overshoot and the small residual vibration. However, the reference model has an oscillation in the plot of the relative distance after 5 sec since the model is continuously updated, unlike the fixed reference model of the previous cases.

In Fig. 12, a synthesized trajectory separated into a flexible-body path and a rigid-body path is used to eliminate the residual oscillation of Fig. 11. By using the path synthesis, no residual vibration on mass m_1 is achieved. However, some oscillation of mass m_2 exists. With sinusoidal disturbance, the simulation results show that the output trend is similar to Fig. 12.

In the parameter estimation of the adaptive cases, the convergence of the estimator must be reasonably fast so that the second place of impulse sequence can be properly determined. As long as the time-varying parameter is asymptotically approaching the true value, the combined method appears to be realizable. Among the three trajectories, the synthesized path could be selected if a stabilizer (Sung, 1997) for the vibration control of the flexible structure is provided to reduce the residual vibration of mass m_2. Through the evaluations, the combined approach appears to be feasible to cope with disturbances, modeling error, and nonlinear effect.

4. Conclusions

The input shaping technique can be used with arbitrary inputs to reduce the residual vibration in maneuvering flexible structures under ideal conditions. However, the input shaping technique is very sensitive with respect to plant modeling such as parameter uncertainty. Moreover, the method cannot be successfully used in the presence of disturbances.

In the proposed approach, an adaptive robust control concept is presented for the vibration reduction of non-ideal flexible spacecraft. The feasibility of the combined implementation of the input shaping technique and the sliding-mode control is presented. The combined approach appears to be efficient and robust in the presence of a severe disturbance and an uncertain parameter. In the maneuver strategy, it is found that a synthesized trajectory which is the combination of a low-frequency mode and a rigid-body mode results in better performance than the rigid-body trajectory alone. The adaptive incorporation of both controllers and the utilization of the system vibration is a distinguishing factor from other methods.

As previously indicated for the one-dimensional flexible spacecraft, the combined technique can reduce the vibration of the flexible structure as well as achieve the attitude control of a rigid body with non-ideal effects. However, a stabilizing ability is required to completely eliminate the residual vibration in applications of the control concept to realistic multi-dimensional flexible spacecrafts. In a realistic system, the control system also faces issues of enormously large system order and multi-input multi-output (MIMO) problems unlike the one-dimensional system.

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