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Performance investigation of variable damping shock absorber combined with conventional semi-active vibration control logics

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ABSTRACT

The shock induced by a rocket lift-off and pyrotechnic device actuation for interstage separation can cause damage to the on-board instruments of a spacecraft when the acceleration generated by the input shock exceeds their allowable acceleration value. The shock can be attenuated by mounting a shock absorber. In this paper, we propose a variable damping shock attenuation strategy combined with conventional semi-active vibration control laws derived from a two elements model composed of variable damping and spring stiffness that would attenuate the shock such that the main instrument's input acceleration does not exceed the allowable acceleration value. The analysis results indicate that the combination of shock and conventional semi-active control logic attenuates the shock level better than an optimal passive and conventional semi-active control system. The strategy is also effective for suppressing the consequent vibration induced by the shock event.

1. Introduction

The excessive shock loads in the several thousands of g's level induced by several shock events during the launch vehicle lift-off can cause permanent damage to the electronics, optics, and other sensitive payload components. These shock events result from stage separation, fairing separation, spacecraft separation, dual launch attach fitting separation, motor ignitions, and motor shutdowns during lift-off. In an orbit condition, shock events are generally induced by deployment events, such as solar arrays and antenna deployment. Almost of these shock events, which can cause critical damage on the sensitive components, are from the actuation of pyrotechnic devices to release a mechanical constraint for deployment or stage separation mechanism. The pyrotechnic devices generally produce a high frequency, high amplitude shock energy due to the sudden release of stored energy at the time of actuation. Some examples of mission failures by excessive shock loads are the breakage of electrical leads and solder joints, the chatter of relay, the slipping of the position sensor, the transient electrical malfunctions in capacitors, the loosening of bolts, damage on the gear, and fractures in brittle components [2].

If the spacecraft and key sensitive components are designed and tested to withstand the harsh shock loads, the cost is greatly increased. An alternative way to reduce the risk of damage on the on-board key components without increasing any costs is to attenuate the shock loads through the use of a shock isolation system. The shock isolation system makes it possible to dramatically reduce the risk of mission failure and the mass of the spacecraft.

A whole spacecraft passive isolation system [1,2,11] has been developed and successfully flown several times in order to attenuate the dynamic loads for some launch vehicles. This shock system, known as the SoftRide ShockRing, is a whole-spacecraft isolation system. The system is a continuous ring made of a series of highly damped flexures. It is located in the stack just after the satellite in order to attenuate all shock loads from the launch vehicle.

Passive systems for shock and vibration isolation have been widely used for space applications because the system, whose dynamic energy is dissipated by structural damping, viscosity, and friction is always stable. Although this robustness of the passive system is a great advantage for space application, the system usually has the disadvantage of damping performance due to the fixed parameters. The passive isolation system with lower damping is effective for shock attenuation. However, the passive system cannot effectively suppress the consequent vibration induced by the shock event and vibration under launch environment since it cannot adapt to environmental changes due to the fixed parameters. An active system is a very attractive and powerful approach for overcoming the disadvantage of the passive system's performance deterioration, but it is costly and its reliability is reduced by unstable phenomena, such as spillover, especially when the exact dynamic characteristics of the structures are not known.

The semi-active approach seems promising for space applications because it has advantages in both passive and active systems.

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The performance of a semi-active system is much better than that of passive systems because the damping force is controlled by the state of the systems such that their inherent damping performances are enhanced. In addition, the robustness of the semi-active system is a great benefit because energy is always dissipated by passive mechanisms.

Several types of semi-active systems using smart materials for space applications have been proposed and studied by many researchers [6–10]. Makihara et al. [4] numerically investigated the performance of a powerful semi-active shock absorber utilizing particle dispersion type ER fluid. The main purpose of the shock absorber was to attenuate shock so that the acceleration of the instruments does not exceed a critical value, even when the shock force input is too large to be accepted. They proposed a shock attenuation logic combined with conventional semi-active vibration control to suppress a consequent vibration induced by the shock. The numerical simulation results indicated that this logic is effective for both shock attenuation and vibration suppression as intended by control law. The shock absorber model proposed by Makihara et al. is a four elements model composed of variable friction, constant damping, and two spring elements. The variable friction element is aggressively controlled by the state of the systems such that the performance of the damping element to dissipate shock and vibration energy is enhanced. However, the variable friction shock absorber is more amplitude dependent than variable damping and it is a disadvantage of the particle dispersion type ER fluid [5].

In this study, we focused on a variable damping shock and vibration control as an extension of the research described in Ref. [4]. The shock control logic, which is more simpler to apply to a two elements model composed of variable damping and spring stiffness elements, was derived and its effectiveness was verified by numerical simulation. In the numerical simulation, the performance of the shock control logics, combined with a conventional skyhook control algorithm, was compared to that of the logic combined with a bang–bang control derived from the LQ theory. The performance of the control logic when the time delay at the time of on–off switching exists was also investigated. Numerical simulation results demonstrate that the shock strategy, combined with the conventional LQ semi-active control law, is effective for dissipating both shock and vibration energy.

2. Variable damping shock absorber

To investigate the effectiveness of the variable damping shock absorber, we used a simple one DoF (degree-of-freedom) model with a constant damping coefficient of c, a variable damping coefficient of c_v, and a spring stiffness element of k, as shown in Fig. 1. We assumed that the variable damping of c_v can be continuously controlled by the electric or magnetic field strength of functional fluids, such as the liquid crystal type ER fluid [6] or MR fluid [10]. The variable damping shock absorber that attenuates the transmitted shock level is located between the shock sensitive on-board component with a mass of m and the base where the half sine shock wave input is applied.

The equation of motion for the numerical simulation model, as shown in Fig. 1, can be written as

$$m\ddot{z} + c\dot{z} + kz = -c_v\dot{z} - m\ddot{y} \tag{1}$$

and the force transmitted to the mass (p) is given by

$$p = -c\dot{z} - kz - c_v\dot{z} \tag{2}$$

where z indicates a relative displacement of x to $y(x-y)$. x and y represent a displacement of the mass m and base, respectively.

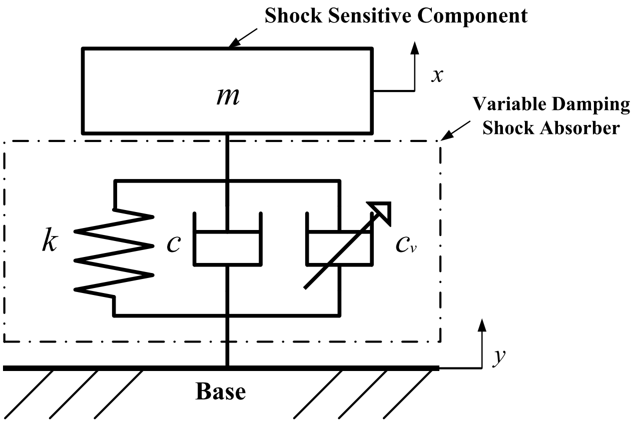

Fig. 1. Numerical simulation model.

3. Shock and vibration control strategies

The main purpose of the semi-active shock absorber proposed in this study is to attenuate shock so that the input acceleration to the shock sensitive components does not exceed the allowable value of the sensitive component, even when the shock force input is too large to be accepted. The shock absorber, combined with conventional semi-active vibration control, is also effective in suppressing the consequent vibration induced by the shock. These approaches can be implemented by variable damping semi-active shock absorbers with the following strategies.

3.1. Semi-active vibration control strategy

The shock sensitive on-board components experience a harsh vibration environment, such as sine and random, during the lift-off. The shock also induces subsequent vibrations after pyrotechnic actuation. These vibrations can be suppressed by the following conventional semi-active control laws.

The conventional skyhook control algorithm suggested by Karnopp [3] can be implemented using the relationship between the absolute velocity and the relative velocity in order to minimize the transmitted energy from the disturbance source to the main sensitive component. If we assume that the variation of c_v is limited to a range from the minimum damping coefficient of $c_{v\,\min}$ to the maximum damping coefficient of $c_{v\,\max}$, the following switching conditions can be derived from the conventional skyhook control strategy:

$$\begin{aligned} c_v &= c_{v\,\min} \quad \text{when } \dot{x}\dot{z} \leqslant 0 \\ c_v &= c_{v\,\max} \quad \text{when } \dot{x}\dot{z} > 0 \end{aligned} \tag{3}$$

In this paper, this strategy is called skyhook control law.

To derive the vibration control strategy based on the Linear Quadratic (LQ) theory, Eq. (1) can be written as the following state space equation:

$$\dot{X} = AX + B\nu + B_d\ddot{y} \tag{4}$$

where,

$$X = [z \quad \dot{z}]^T \tag{5}$$

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix} \tag{6}$$

$$B = [0 \quad -\tfrac{1}{m}]^T \tag{7}$$

$$B_d = [0 \quad -1] \tag{8}$$

and

$$\nu = c_v\dot{z} \tag{9}$$