PRE-ACTING IMPACT ISOLATION SYSTEMS

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Summary The pre-action control concept is considered as applied to impact isolation systems. The limiting performance analysis is performed for a single-degree-of-freedom system subject to an instantaneous impact. A substantial advantage of pre-acting isolators is established, as compared with isolators without pre-action. A pre-acting isolator based on a passive elastic element (spring) is suggested. The optimal parameters of this isolator are calculated.

INTRODUCTION

Impact isolators are normally start responding to an impact only after this impact has occurred. In fact, the impact itself serves as a signal for the isolation system to be engaged. In a number of cases, one can predict the initiation time of the impact and its characteristics. In this case, the isolation system can start operating ahead of time, before the impact has occurred. Such isolation systems can be referred to as *pre-acting isolation systems*. In the present paper, we analyze the limiting performance characteristics of pre-acting impact isolators as compared with those of isolators without pre-action. This analysis is performed for a single-degree-of-freedom model in the case of an instantaneous impact. Pre-acting isolators are shown to be able to considerably improve the isolation quality.

LIMITING PERFORMANCE PROBLEM

Consider a SDOF model of a shock/impact isolation system. The object to be protected is connected to the base by means of an impact isolator treated as a controller that generates a control force between the base and the object. The motion of the object relative to the base is governed by the differential equation

$$m\ddot{x} + u = mv, \quad v = -\ddot{z}, \tag{1}$$

where m is the mass of the object, x is the displacement of the object relative to the base, z is the displacement of the base relative to an inertial reference frame and u is the control force applied to the base (accordingly, $-u$ is the control force applied to the object). The variable v characterizes the disturbance of the base induced by an impact. Consider the optimization problem.

Problem. Let the motion of the object relative to the base be governed on the time interval $[-t_0, \infty)$, $t_0 \geq 0$, by Eq. (1), where $v = v(t)$ is a prescribed function of time, which is identically zero for $-t_0 < t < 0$. Let this system be subject to zero initial conditions

$$x(-t_0) = 0, \quad \dot{x}(-t_0) = 0. \tag{2}$$

It is necessary to find an optimal value t_0^* and a control $u_0(t)$ that is defined for $t \geq -t_0^*$, satisfies the constraint

$$|u_0(t)| \leq U, \tag{3}$$

where U is a prescribed positive constant, and minimizes the peak absolute value of the relative displacement of the object to be protected, i.e.,

$$J(u_0, t_0^*) = \min_{u,t_0} J(u, t_0), \qquad J(u, t_0) = \max_{t\in[-t_0,\infty)} |x(t; t_0, u)|. \tag{4}$$

The notation $x(t; t_0, u)$ stands for the solution of the initial value problem of Eqs. (1) and (2) for a specified control $u = u(t)$. The instant $t = 0$ is identified with the time at which the impact pulse starts acting and t_0 is the time before the impact since which the control is allowed to act (pre-action time), and U is the maximum magnitude of the force allowed to be transmitted to the object by the isolator.

This problem is frequently referred to as the *limiting performance problem*, since its solution yields the absolute minimum of the performance index that can be reached irrespective of the specific design configuration of the isolation system.

In what follows, we will consider an instantaneous impact for which $v(t) = v_0\delta(t)$, where $\delta(t)$ is Dirac's delta function and v_0 is a positive number equal to the velocity increment imparted to the object by the impact. Then the solution of the limiting performance problem yields

$$J(u_0, t_0^*) = \frac{mv_0^2}{16U}, \quad t_0^* = \frac{mv_0}{U}. \tag{5}$$

In the case of the control without pre-action ($t_0 = 0$), the minimum value of the criterion J is 8 times that of Eq. (5).

PARAMETRIC SYNTHESIS OF A PASSIVE PRE-ACTING IMPACT ISOLATOR

A pre-acting impact isolator can be designed with a passive elastic element (spring). The pre-action operation of such an isolator can be provided by pre-straining (cocking) the spring and releasing it at an appropriate time instant before the impact. The preliminary strain and the time of its release are to be determined so as to provide the maximum effectiveness of the isolator. Let the spring have a power-law characteristic. In this case, $u = k|x|^n \operatorname{sign} x$ and the relative motion of the object is governed by the equation

$$m\ddot{x} + k|x|^n \operatorname{sign} x = 0, \quad n \geq 0, \tag{6}$$

where k is the stiffness coefficient of the spring. At the instant of the release of the spring, $t = -t_0$ (for t_0 time units before the impact), the object has been moved to the position $x = a$ (the spring has been cocked) as is in a state of rest. Accordingly, we have the initial condition

$$x(-t_0) = a, \quad x(-t_0) = 0. \tag{7}$$

At the impact instant $(t = 0)$, the relative velocity of the object jumps by v_0, which is expressed by the additional condition

$$\dot{x}(+0) = \dot{x}(-0) + v_0. \tag{8}$$

The optimal values of the parameters k, a, and t_0, chosen so as to minimize the peak magnitude of the relative displacement of the body under the constraint $|u| \leq U$, are

$$k = \left[\frac{8}{(n+1)mv_0^2}\right]^n U^{n+1}, \quad a = \frac{(n+1)mv_0^2}{8U}, \quad t_0 = \frac{mv_0}{4U} \mathrm{B}\left(\frac{1}{n+1}, \frac{1}{2}\right), \tag{9}$$

where $\mathrm{B}(\xi, \eta)$ is the beta-function (Euler's integral of the first kind). The corresponding minimum of the peak displacement of the object is $J = (n+1)mv_0^2/(8U)$. This value decreases as n decreases, and in the limit as $n \to 0$, we have $J = mv_0^2/(8U)$, which is by a factor of 4 less than the peak displacement corresponding to the limiting performance of isolators without pre-action and by a factor of 2 greater than the value of Eq. (5) characterizing the limiting performance of pre-acting isolators.

CONCLUSIONS

In the cases where one can predict the initiation time and the characteristics of the impact, it is reasonable to utilize pre-acting impact isolators that start responding to the impact before it has occurred. For a single-degree-of-freedom model subjected to an instantaneous impact, pre-acting isolators can provide a factor of 8 reduction in the peak absolute value of the displacement of the body to be protected, as compared with the limiting performance characteristics of isolators without pre-action. A factor of 4 reduction can be provided by a spring isolator, if one pre-stains the spring and then releases at an appropriate time instant before the impact. Pre-acing isolators can be effective in injury prevention systems on road and air transportation vehicles. This is the case, for example, for an aircraft ejection seat. The time history of the acceleration of the ejection seat after shooting (impact pulse) is known. One can introduce a small time delay between the instant of switching on the system and the instant of the beginning of the acceleration to enable the injury prevention system to get prepared to respond to the impact. Pre-acting isolators can be utilized on helicopter seats to reduce the severity of injuries in the case of hard vertical landing. By measuring the altitude and the descent velocity of the helicopter, one can calculate the instant and velocity of the impact ahead of time. Isolators of this type seem to be promising for utilizing in automobile safety systems.