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Shock Isolation Parameters Based on a Damped Harmonic Oscillator Model for Mine Blast Protected Seating

by Brendan McAndrew

ARL-TR-4236 **September 2007**

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14. ABSTRACT
Shock isolation parameters for mine blast resistant seating are developed based on a damped harmonic oscillator model. Required seat stroke allowance for different vehicle types and blast impulse levels is provided. Optimal solutions are presented for minimizing acceleration and Dynamic Response Index (DRI), as well as the corresponding acceleration profiles. The DRI limits are shown to be more restrictive than acceleration limits found in the literature.

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Mine blast; DRI model; shock isolation

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1. Introduction

External armor protects vehicles from the high temperatures, blast overpressure, fragmentation, and debris generated by the explosion of land mines. However, a combination of air blast, fragments, and soil ejecta also delivers an impulsive load to the underbody of a vehicle. This impulse is imparted in a few milliseconds (ms), resulting in high initial acceleration. Mechanical isolation between the occupants and the vehicle is required to reduce the acceleration to acceptable levels for survivability. A well-designed mine blast protected vehicle should provide survivable mechanical isolation for the occupants up to the threat levels for which the armor was designed. This can be achieved by allowing for adequate seat stroke, or displacement of the seat relative to the vehicle, and by incorporating appropriate shock isolation between them.

This report reviews some background information regarding vehicle blast response, presents minimum seat stroke requirements, provides an overview of the Dynamic Response Index (DRI) model, and explores implications of this model for spinal injuries. Guidelines for shock isolation parameters to achieve minimum DRI and minimum acceleration are developed for a damped harmonic oscillator.

2. Blast Loading and Vehicle Response

Vehicle rigid body motion (e.g., motion of the center of gravity), is determined by the blast loading and the mass of the vehicle. In turn, blast loading is dependent upon the burial depth of the charge and soil conditions. For a surface laid explosive, the blast wave propagates as a hemispherical wave outward from the detonation point. Buried explosives produce more concentrated loading inside a debris cone. Shallow buried explosives concentrate most of their blast effects on the vehicle, where the standoff from the explosive charge to the vehicle underbody is much less than the length or width dimensions. Deep buried explosives apply a smaller portion of their impulse to the vehicle because the debris cone is larger than the vehicle dimensions. Shallow buried explosives are therefore the most efficient at coupling momentum, and represent the worst case blast loading for shock isolation.

Larger vehicles are less vulnerable due to their increased mass. Their larger underbody area contributes only weakly to the impulse delivered, because even vehicles of relatively modest size can intercept the majority of the debris cone. Increased ground clearance is beneficial due to the drop off in blast loading with distance. Figure 1 is a plot of rigid body motion attained by vehicles of various mass against the impulse levels achievable with shallow buried explosives. Local velocities may be higher due to off-center blast loading or dynamic deflection of the hull.

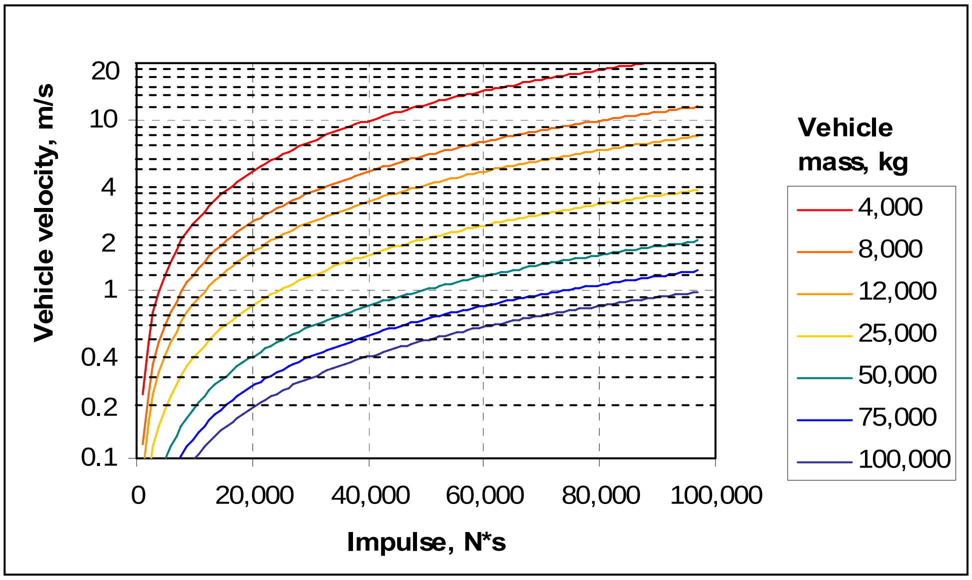

Figure 1. Rigid body velocity attained by vehicles subjected to impulsive loading.

As a conservative approximation, the vehicle velocity shown in figure 1 may be assumed to be acquired instantaneously. To protect the occupants against unacceptably high acceleration loads, the seat design must allow for relative motion with the vehicle. The shock absorbing system must cancel this relative motion between the occupant and the vehicle while applying survivable acceleration loads. A greater distance between the seat and vehicle hard points will allow for a more gradual acceleration profile; conversely, tighter space constraints will require higher acceleration to match the vehicle velocity within the available distance. The distance required for motion between the vehicle and the seat with a constant acceleration is given by

$$d = \frac{v^2}{2a}, \tag{1}$$

where d is distance, a is acceleration, and v is the vehicle velocity. Using the relationship between velocity and impulse shown in figure 1, the required seat stroke for a constant acceleration can be plotted as a function of vehicle mass and applied impulse. An example of this is shown in figure 2. Notice that the required seat stroke scales with the square of impulse and inversely with the square of mass, becoming a particularly important design consideration for lightweight vehicles.

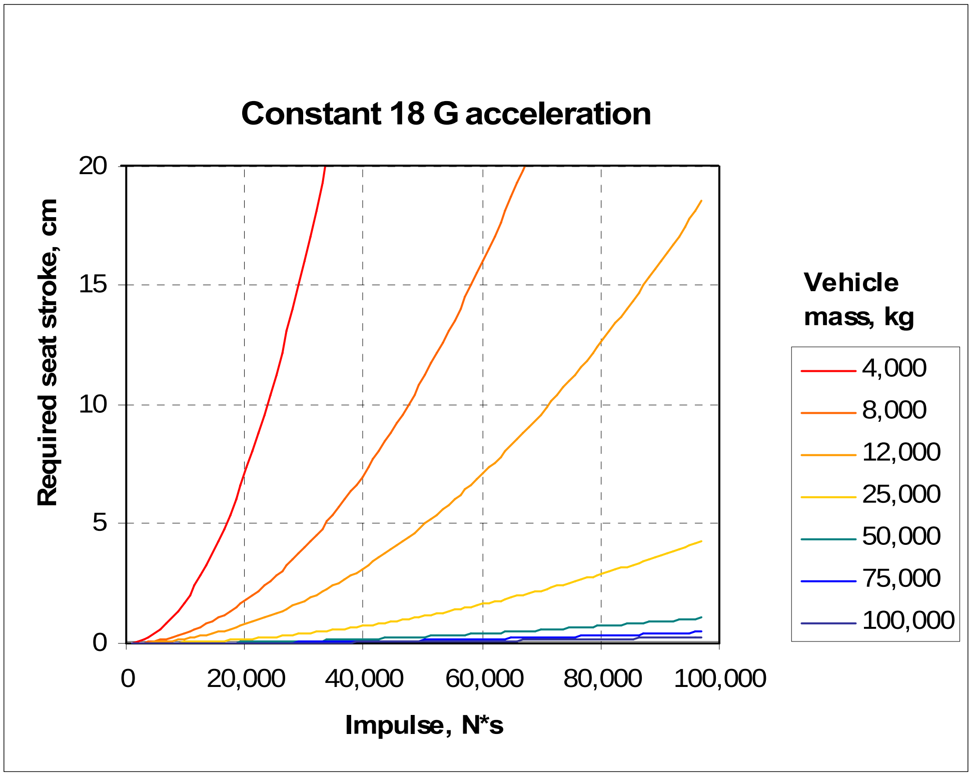

Figure 2. Seat stroke required to maintain 18 G acceleration.

3. Occupant Response

Blast overpressure and fragmentation hazards are mitigated by armor, and preservation of the occupied space is maintained by the strength of the vehicle structure. However, rigid body acceleration remains a potential injury mechanism for occupants regardless of the survivability of the vehicle itself or the protection it provides from external hazards (*1*,*2*). The North Atlantic Treaty Organization (NATO) coordinate system used for body coordinates is +x in the forward direction, +y laterally to the right, and +z in the upward direction. This coordinate system convention does not obey the right-hand rule. Under +z acceleration, the primary injury mechanism for serious injuries is due to compressive loading of the spinal column (*3*). The response of the human body to various acceleration loads has been investigated in detail in a number of prior works, including a comprehensive review of available data in 1959 by Eiband (*4*). Eiband recommended a +z acceleration limit of 23 G applied for 5.5 ms based on catapult tests. This time limit was later increased to 25 ms based on helicopter crashworthy seating design work (*5*). Acceleration limits were further relaxed in reference (*2*), with a limit of 25 G applied for 100 ms. Notice that these acceleration limits apply to well-restrained young males.

4. DRI Model

The DRI model was developed to characterize the response of the spinal column to short duration accelerations. It was originally developed to aid in aircraft ejection seat design, and has since been extended for use in crashworthiness and mine blast studies. Its parameters have been validated through aircraft ejection seat studies, catapult tests, and drop tests (*3*,*6*). At the time of this writing, however, its utility for predicting injury sustained from blast loading has not been validated. The model treats the spine as a lumped mass spring system, with the probability of injury related to the compression of the spine, δ. Therefore, the DRI model takes the form of the forced harmonic oscillator equation

$$\frac{d^2\delta}{dt^2} + 2\zeta\omega_n \frac{d\delta}{dt} + \omega_n^2\delta = \frac{\partial^2 z}{\partial t^2}, \tag{2}$$

where z is the input displacement in the vertical direction. The natural frequency, ω_n, and the damping ratio, ζ, are empirically determined constants with values of 52.9 rad/s and 0.224, respectively (*7*). The non-dimensional DRI is defined as

$$DRI \equiv \frac{\omega_n^2\delta_{\max}}{g}, \tag{3}$$

where g is the acceleration of gravity. Ejection seat and rocket catapult experiments with cadavers and operational ejection seat data have shown the probability of injury to scale exponentially with increasing DRI, with a recommended limit of 18 for the prevention of spinal injuries. It should be emphasized that this model only considers vertical accelerations, and that injury rates rise when the acceleration vector is more than 5° from vertical (*7*).

5. Optimal Solutions

Given an initial velocity change to the vehicle, the minimum acceleration is achieved by applying a constant square pulse acceleration profile over the full available seat stroke. Energy absorbing systems consisting of crushable or permanently deformable components can get close to square pulse acceleration and minimum stroke, but the same acceleration is applied to both large and small velocity changes. The crushable element is also a single use component, and may fail to provide adequate isolation when the vehicle falls back to the ground. This second impact is known as the slam-down phase, during which it is equally important to provide adequate occupant isolation (*1*). A system incorporating a restoring force to return the seat to its initial position may be desirable; enabling the use of the full available seat stroke for both the initial mine blast event as well as the subsequent slam-down.

In addition to the maximum applied acceleration, the DRI depends on the change in acceleration with time. In the case of an undamped harmonic oscillator, a step change in acceleration will produce an overshoot of twice the average value. As damping increases, the ratio decreases, becoming equal to unity at critical damping. Figure 3 illustrates this reduction in overshoot with increasing damping ratio. The damping ratio for the human spine is 0.224, which leads to a maximum spinal compression nearly 50% higher than the steady-state value, as shown in the figure.

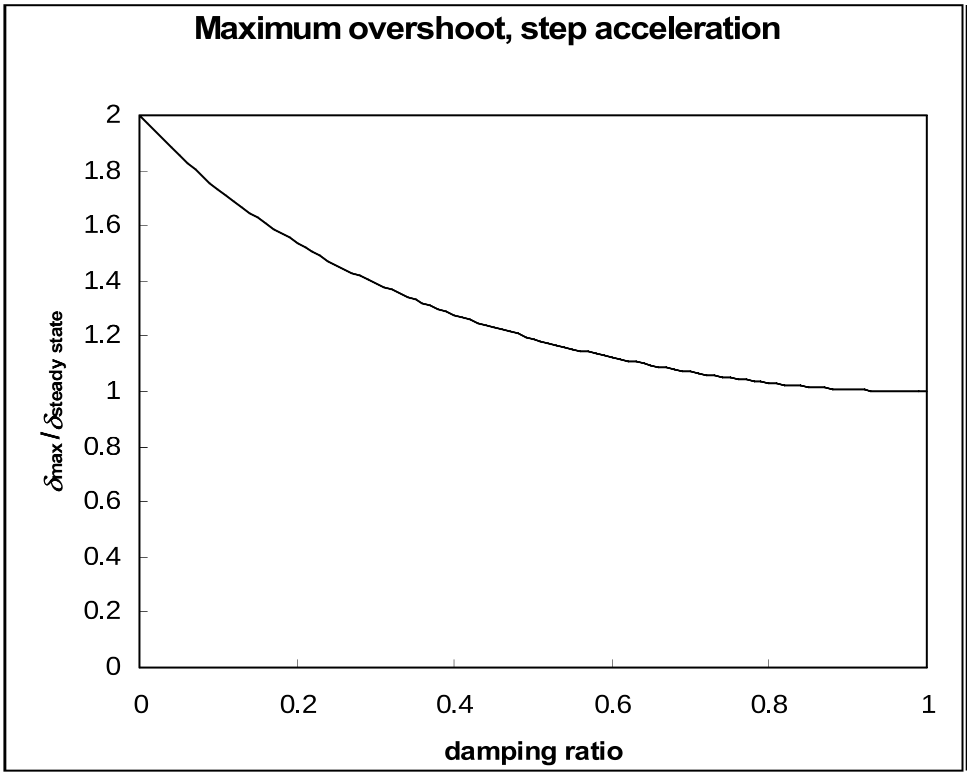

Figure 3. Maximum dynamic compression due to a step acceleration change.

The overshoot can be reduced by ramping up to the maximum acceleration more gradually as in figure 4. Unfortunately, the time required to produce a significant reduction, on the order of 100 ms, results in excessive seat displacement for typical vehicle configurations.

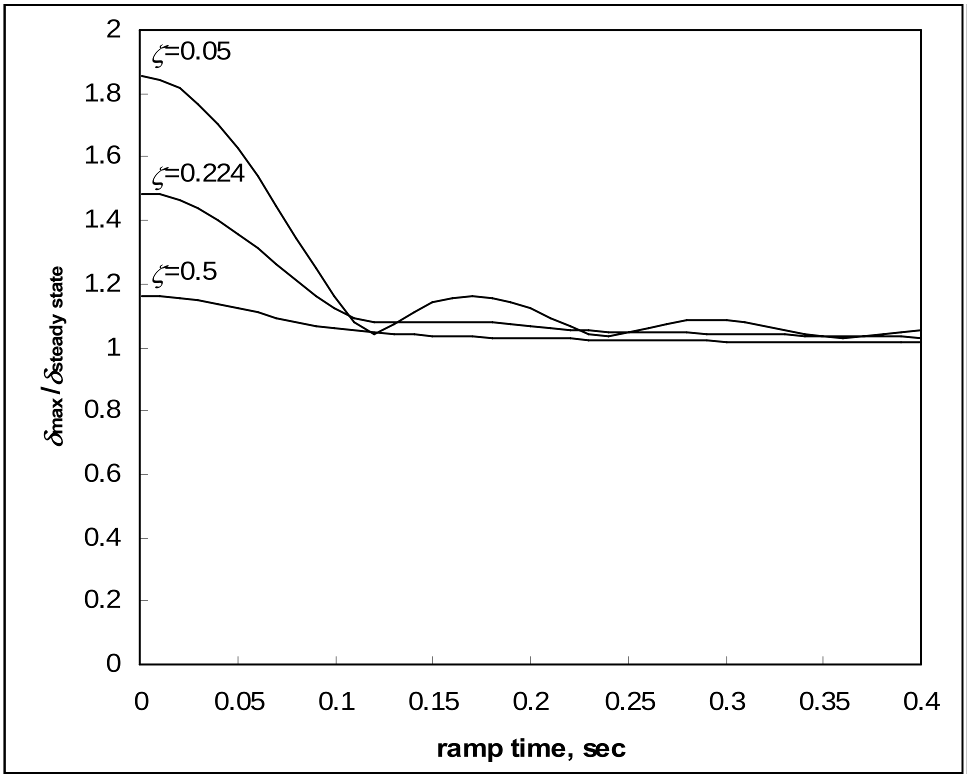

Figure 4. Maximum dynamic compression due to a linear change in acceleration followed by constant acceleration.

Figure 5 shows the time dependent spinal response due to various ramp rates.

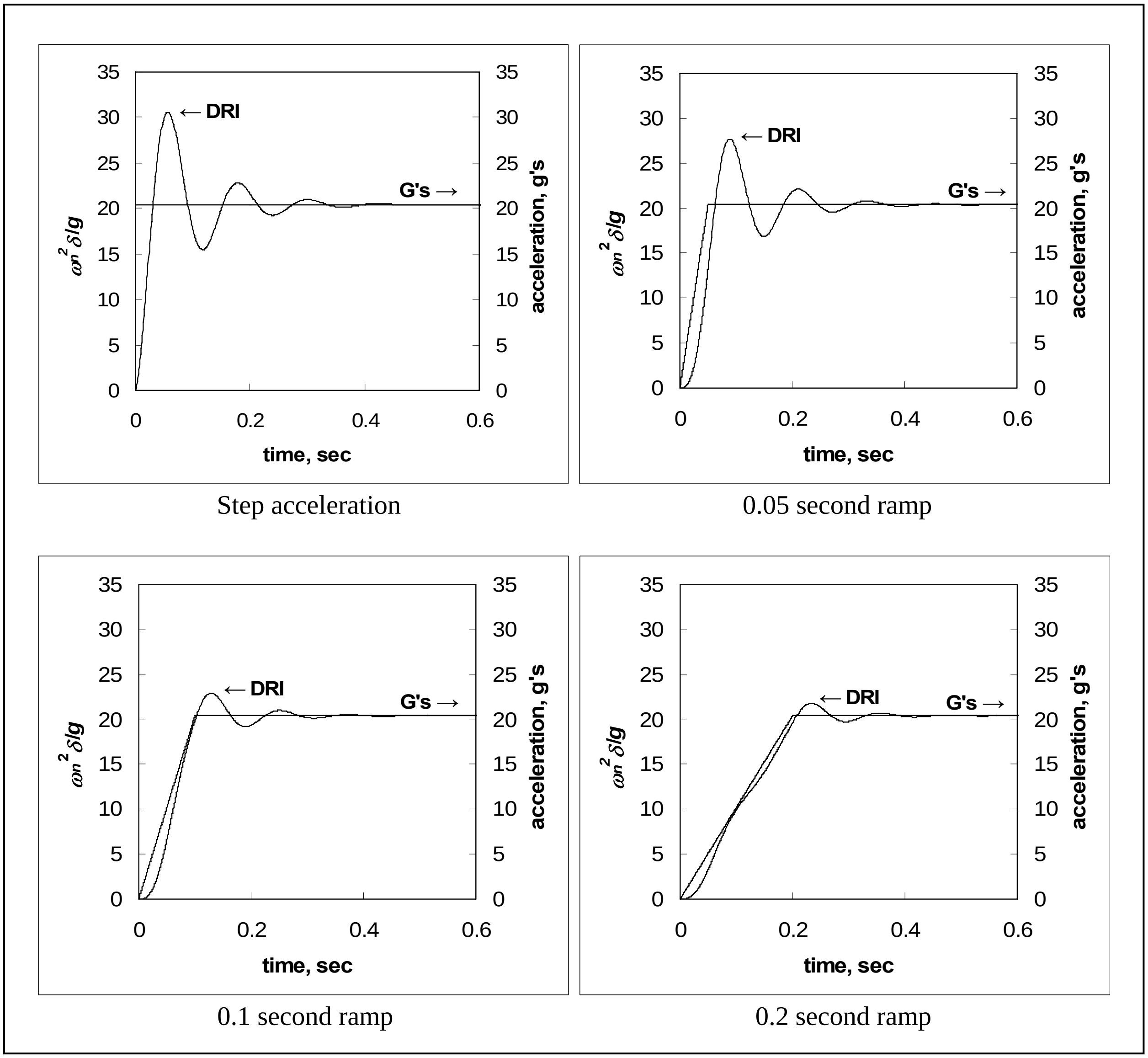

Figure 5. Dynamic overshoot with different acceleration ramp rates.

6. Design Curves

The vehicle internal layout limits the available seat stroke. An optimal acceleration profile should minimize acceleration or DRI to match vehicle velocity with a constant seat stroke constraint. Due to the overshoot effect described above, minimum acceleration and minimum DRI may not be achieved with the same acceleration profile.

Consider an isolated seat that can be modeled as a damped harmonic oscillator. Adjustments to the damping coefficient and spring constant will enable both velocity and seat stroke to be matched. As an example, suppose this is desired for a velocity of 6.26 meters per second (m/s), an allowable seat stroke of 10.3 cm, and a sprung mass of 120 kg. The velocity corresponds to a drop from a height of 2 m. The set of all possible solutions to this example is represented by the curve plotted in figure 6, with resultant maximum acceleration and DRI given in figure 7. The acceleration and DRI are minimized with different oscillator parameters. The acceleration and displacement profiles for these two cases are shown in figure 8. The minimum acceleration occurs with an underdamped oscillator, a potentially undesirable response due to the resultant negative G loading. It is important that the natural frequency of the oscillator remains below the natural frequency of the spine to avoid resonance. In figure 7, DRI rises sharply at higher oscillator frequencies due to this effect.

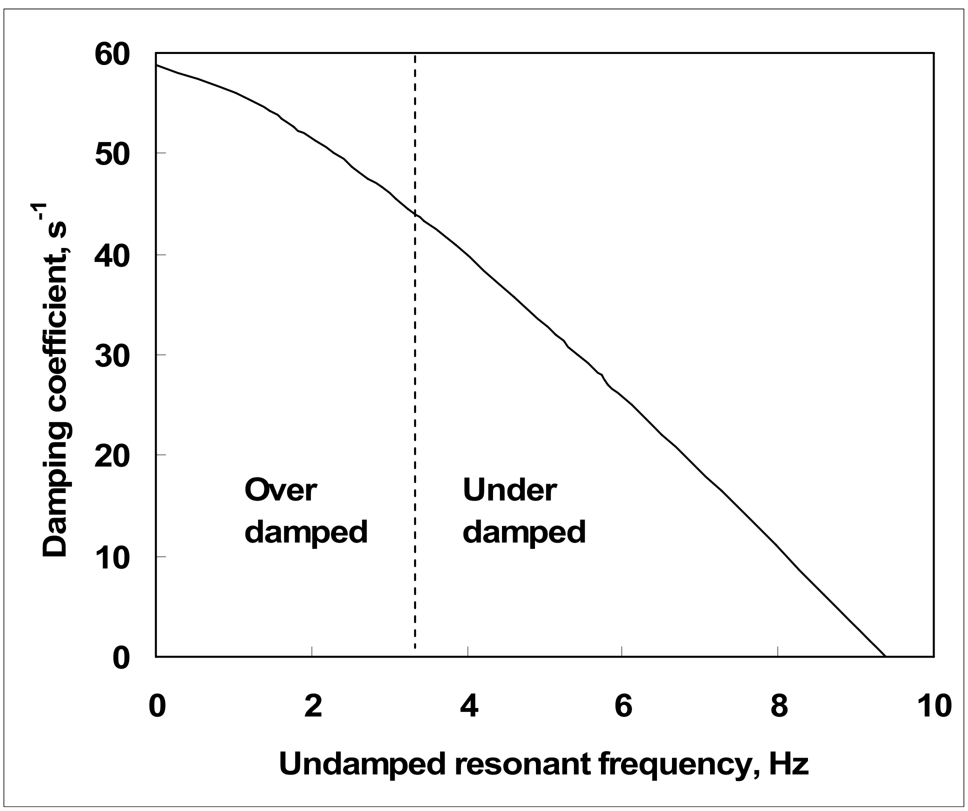

Figure 6. Damped harmonic oscillator parameters giving constant displacement of 10.6 cm with an initial velocity of 6.26 m/s.

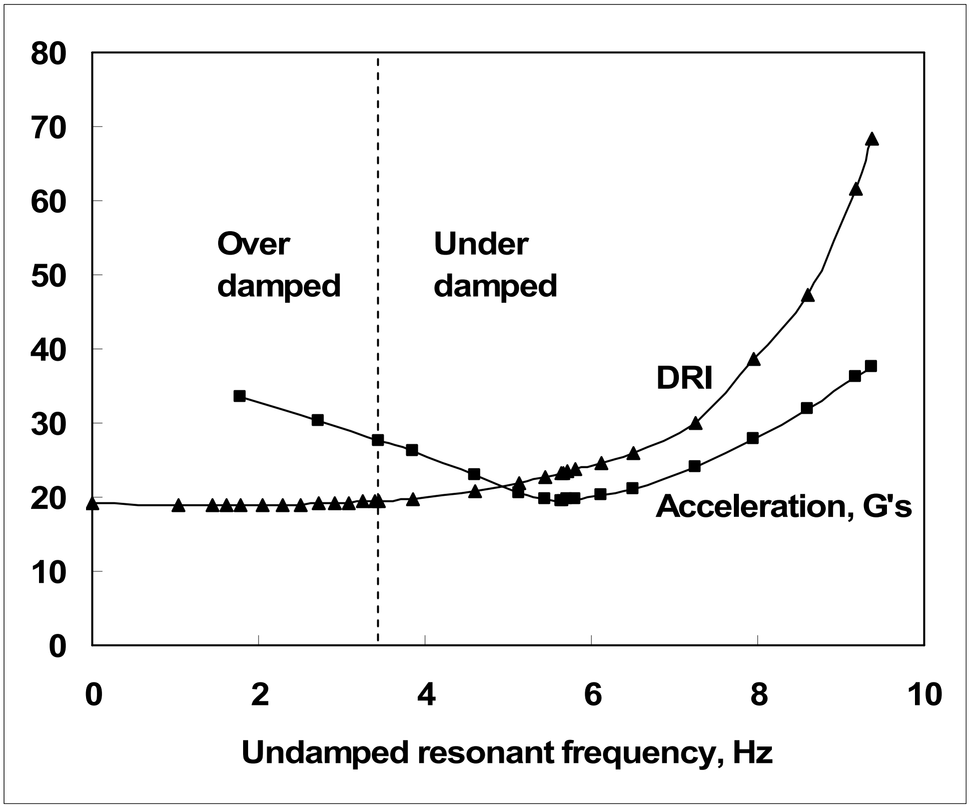

Figure 7. Maximum acceleration and DRI at selected oscillator parameters lying along the constant displacement curve shown in figure 6.

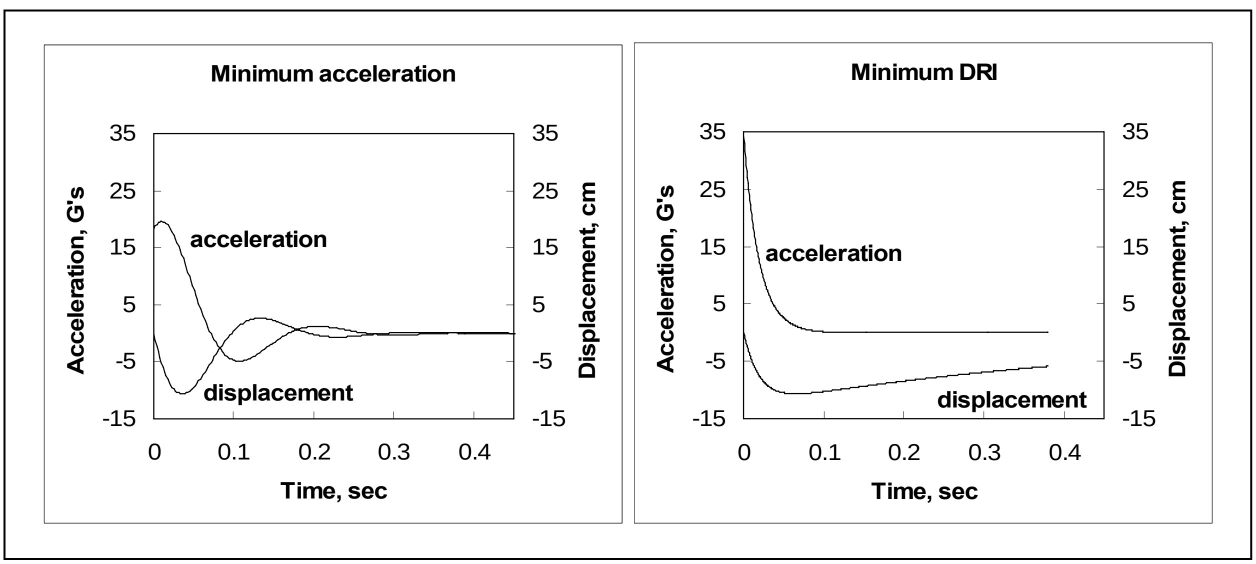

Figure 8. Acceleration profiles for minimum acceleration and minimum DRI.

7. Conclusions

Shock isolation should be matched to the vehicle mass and protection level provided by the armor to ensure occupant survivability. Minimum acceleration and minimum DRI, for a given velocity change and allowable seat stroke, are not achieved with the same acceleration profile; therefore, any shock isolation system will be a compromise. Care must be taken in an underdamped system because seat restraints and overhead clearance become critical. Overdamped or critically damped systems have lower DRI, but a much higher G loading for the same seat stroke. Square pulse acceleration provides minimum G loading, but not minimum DRI, and does not provide a restoring force for the slam-down phase. The short time scales of mine blast events result in DRI overshoot. The dynamic overshoot in spinal compression, $\delta_{max}/\delta_{steady\ state}$, depends on the time scale of the loading function, but is independent of amplitude. The DRI limits recommended in the literature are more restrictive than the recommended acceleration limits. Adequate space for seat displacement is particularly important for lightweight vehicles.

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Acronyms and Abbreviations

DRI	Dynamic Response Index
G	unit of acceleration equal to 9.8 meters per second per second
NATO	North Atlantic Treaty Organization
ms	millisecond
m/s	meter per second
rad/s	radian per second

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