INTRODUCTION TO SHOCK AND VIBRATION ISOLATION AND DAMPING SYSTEMS

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ABSTRACT

Oftentimes a dynamic system or structure requires that it be analyzed for performance or structural suitability within the context of a shock and vibration environment. This paper provides an outline of various applications and methods of implementing isolation, shock absorbing and damping within a wide array of dynamic systems and structures. Successful integration of these useful tools is essential when solving problems within the world of shock, vibration, and structural control. The theory, analytical techniques, and options for hardware selection are often complex tools. Therefore, it is essential that the analyst and the systems engineer be equipped with a basic understanding of control schemes and isolation system attributes that have been proven effective and reliable in a wide variety of shock and vibration isolation applications in the past.

Specifically, key definitions are presented that are widely used within the shock and vibration community. Additionally, useful formulae are presented that will provide the user with an initial path forward with respect to solving typical problems. Finally, a comparison of different types of shock isolators, shock absorbers and dampers will outline their specific advantages and disadvantages when using them for typical applications within the commercial, military, and aerospace sectors.

INTRODUCTION

For many decades, shock and vibration has been modeled and analyzed using a variety of techniques, algorithms, formulae, and empirical data. In most scenarios where shock and/or vibration are present, it is generally undesirable. Sometimes, the shock and vibration environment is unavoidable but can be tolerated. Other times, it is intolerable. In either case, this environment must be analyzed to some degree to determine its acceptability. When the environment is deemed to be intolerable, the issue must be addressed through discrete changes that will make the environment acceptable. When this is not possible or practical, shock and vibration must be controlled through mitigation. Mitigation often includes the integration of special hardware including shock absorbers, dampers, vibration isolators, shock isolators, shock transmission units, etc.

Currently, high speed computers, in conjunction with finite element programs and analytical software codes, have revolutionized the capability and methods for accurately modeling physical products, structures and mechanisms under dynamic environments and for optimizing practical solutions as necessary. Much has been written about the methods employed by analysts and engineers for predicting the performance of these systems. However, these methods and solutions are limited by the information available to the analytical community with respect to the practical hardware that helps solve these problems. For example, special dampers, isolators, and shock absorbers have been successfully developed and integrated into dynamic systems that possess unique output functions with respect to the response they provide to these dynamic environments. Some of these products and their features have been used extensively and are well known. Some are not well known. This paper will review the basic problem at hand, list some common formulae used for various problems, provide commonly used definitions, and will attempt to provide some special features that are available to the community at large. Simply stated, as noted in the abstract of this paper, it is essential that analysts and systems engineers be equipped with a full database of damper, shock absorber and isolation system attributes that have been proven effective and reliable in the past.

GENERAL HARDWARE DEFINITIONS

For the purposes of this paper, hardware that mitigates shock and vibration can be categorized into three main groups as follows:

Isolators

Isolators de-couple (or isolate) to some degree the input energy from a protected mass or structure. Some of this energy does filter through typical isolation systems, but isolator output parameters are normally optimized to reduce the response to a pre-determined acceptable level. Isolators do not necessarily aim to absorb as much energy as possible, but rather to cause the dangerous input energy to bypass the isolated mass as much as possible. Most isolators consist of a combination of spring and damping components of some type.

Shock isolators generally aim to minimize the reaction force (acceleration) to a protected mass during a transient shock event within determined acceleration and/or position constraints. These shock events are often quantified in terms of a time history (position, velocity, or acceleration versus time.)

Vibration isolators generally aim to reduce the reaction force (acceleration) of a protected mass during a continuous vibration environment usually caused by an external power influence. Random vibration *input* is sometimes quantified by a PSD (Power Spectral Density), ASD (Acceleration Spectral Density), or G_{rms} (root mean square of acceleration.) PSD and ASD effectively quantify the level of vibration over a given frequency range, limited by the power source, in terms of G^2/Hz. The vibration *response* of a mass subjected to this environment is often quantified by the ratio of the acceleration input to the response acceleration (transmissibility or TR), or decibels (db). Refer to Equations 1, 2 and 3 below:

$$G_{rms} = \sqrt{}\ (\text{PSD x } \Delta \text{ frequency range}) \qquad (1)$$

$$\text{TR (transmissibility)} = G_{response} / G_{input} \qquad (2)$$

$$\text{db (decibels)} = 20 \text{ x } \log \text{TR} \qquad (3)$$

Figures 1 and 2 for example, illustrate the vibration response of a mass subjected to a random vibration input level of .04 G_{rms} over a frequency range of 0 to 200 Hz. Figure 1 demonstrates effective isolation, since the transmissibility is typically well below 1 and generally decreases as frequency increases. This effect is referred to as frequency roll-off. Simple isolators with a linear damping relationship will provide some level of roll-off. However, some specialized vibration isolators can provide a high level of roll-off, thereby effectively reducing the energy input to the isolated mass over a wider frequency bandwidth. Naturally, some other isolator non-linearities such as isolator friction can further sacrifice system performance. Figure 2 demonstrates ineffective vibration isolation due to the fact that there exists a high level of transmissibility (amplification) at 2 discrete frequencies.

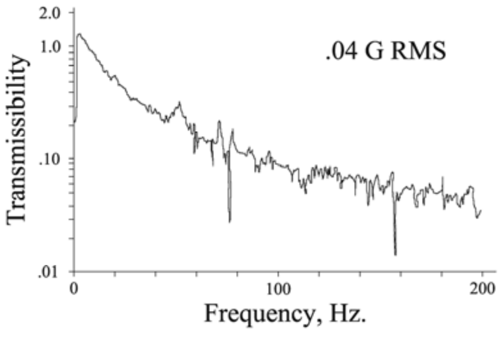

Figure 1

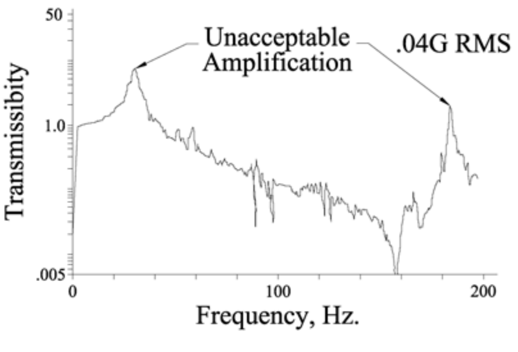

Figure 2

Note that in Figure 1 even optimized passive random vibration isolators have a transmissibility of greater than 1 at one discrete frequency. This represents the natural frequency (resonance) of the system. The amount of damping that exists in the isolator provides a trade-off between transmissibility at resonance and the transmissibility at all other frequencies. A low damping level will generally provide a relatively low TR over a wide bandwidth but a relatively high TR at resonance. Conversely, a high damping level will generally provide low TR at resonance but will sacrifice performance over the remaining frequency range. These are general rules, for indeed there are some very specialized vibration isolator designs available that do provide variable characteristics over the entire frequency range, thereby optimizing performance for the protected mass.

Vibration isolators for simple harmonic or sinusoidal input are somewhat less complex to predict and integrate into dynamic systems in need of mitigation. Standard algorithms exist and isolation hardware is readily available for a variety of applications.

Dampers

Dampers aim to continuously remove energy from a moving system to control its response through the reduction of velocity, relative motion and/or mechanical strain. Most dampers react with a force that is a function of velocity. Some dampers react with a force that is a function of position as well as velocity.

Shock / Energy Absorbers

Shock absorbers typically aim to absorb a maximum amount of kinetic energy and sometimes potential energy, usually in the most efficient manner possible, and to bring a moving mass to a stop with minimal force or deceleration. Many shock absorbers consist of a combination of spring and damping components.

These definitions are not absolute. They are presented here in an attempt to define their intended function in a specific application. There exists some overlap in the categorization of these items. For instance, isolators and shock absorbers sometimes consist of a combination of dampers and springs. Other times, a damper can be used exclusively to absorb shock. But whatever the application, these items all contribute to the mitigation of shock and vibration and result in benefits including a reduced response acceleration, reduced deflection and stress, reduced component weight, improved bio-dynamics, longer fatigue life, architectural enhancement, or reduced cost.

ISOLATORS AND ISOLATION SYSTEM COMPONENT HARDWARE

Isolation systems can be categorized into four main types as follows:

Passive - Isolation system component parameters are fixed and do not change with varying input.

Adaptive - Isolation system component parameters are adjusted by internal mechanical, hydraulic, or electronic means to change the passive parameters. These also include components that mechanically react to varying input. Typically the internal control system, regardless of its complexity, alters parameters following a defined path.

Semi-active - Isolation system parameters change based on input to an excitation sensing element but do not drive the system with an internal power source. Typically, some sort of feedback control scheme is used.

Fully active – Traditional isolation components are replaced with force driving elements powered by an external source. This type of isolation requires a complex and usually redundant control system to ensure both optimal performance and reliability.

Typical isolation systems consist of elements including springs, dampers, actuators, and sometimes additional mass in some form.

SPRINGS

There are many types of springs. Springs react with force as a function of position or deflection. Many mechanical springs provide a force that is directly proportional to the amount of deflection. These are linear springs and obey Equation 4:

$$\text{Force} = \text{Spring Rate} \times \text{Deflection, or } F = KX \tag{4}$$

Other springs are non-linear and obey a variety of different relationships with respect to spring force versus deflection. Some springs even change their characteristics as a function of frequency or velocity. This is sometimes referred to as the dynamic stiffening factor. Springs that have a rate near zero are referred to as constant force or negator springs since their force is virtually unchanged with a changing deflection. Some types of springs are listed below:

Wound (Coil) Springs – Advantages include low cost, long life, very predictable performance, readily and quickly available. Disadvantages include inherent instabilities, difficult to fixture into a stable condition, and poor availability in very large sizes and force levels.

Machined Springs – Advantages include compact package, no practical size limitations, extreme accuracy, inherent stability, and the ability to incorporate attach points for any type of mechanism. The main disadvantage is their high cost.

Elastomer Springs – Advantages include low cost and moderate life under corrosive environments. Disadvantages include relatively high temperature dependency, size limitations, and sometimes undesirable non-linear behavior.

Pneumatic Springs – Advantages include compact designs and moderate life. Disadvantages include relatively high temperature dependency and size limitations.

Liquid Springs – Advantages include very compact designs, moderate life, and the ability to add high damping levels. Disadvantages include temperature dependency and relatively high cost.

Springs can be designed into a dynamic system to provide the following types of arrangements:

Un-centered – Displacement of the system changes with the addition of load. A typical example is the spring of an automobile suspension.

Soft-centered – One or more springs are used to position the isolated mass to a neutral position. The removal of any external force will cause the system to move back towards this position. However, any system friction will prevent the return to an accurate position.

Hard-centered – The spring is preloaded to provide a means of returning the system to its initial condition and to prevent any movement under relatively low input levels.

DAMPERS

Damping is a critical tool in shock and vibration isolation. Dampers can be designed to react with force as a function of relative velocity, position, in some cases frequency, or combinations thereof. Types of dampers include hydraulic or viscous dampers, coulomb or friction dampers, elastomer dampers, structural damping materials, and tuned mass dampers, among others. The attributes of various damper types are outlined further below.

Linear Damping Function:

Determining the level of damping or determining the optimal damping relationship for a given application can be a complex process. Some applications can benefit greatly by adding a level of damping consistent with proven techniques that do not require a highly complex optimization process. For oscillating sprung mass systems, the amount of damping is often characterized as a percentage of critical damping. The critical damping level is defined as that amount of damping that would cause a sprung mass to slowly come to an equilibrium position without overshooting that position (or oscillating). Mathematically, critical damping follows Equations 5 and 6:

$C_{critical} = 2 \times \omega \times \text{mass}$, where ω is in radians per second (5)

$C_{critical} = 2 \times \sqrt{(K \times \text{mass})}$, where K is the system spring rate as defined above (6)

Inherent in the equations above is that the resulting C value is in units of force-time/displacement and this implies a linear relationship between damper force and velocity. Therefore, it follows that the damper output function obeys the following equation:

Damper Force (lbs) = C (lbs-sec/in) x Velocity (in/sec) (7)

As a point of reference, many automotive suspensions have dampers with 20-25% of critical. Truck suspensions might typically have 30-40% of critical. Damping used for the suppression of weapons shock in military applications is not normally categorized in terms of percent damping. However, these applications might use a level of 2000% or more depending on many variables and often require a higher level analysis to provide an optimal solution.

Non-Linear Damping Function:

Dampers that follow Equation 7 have been successfully designed and manufactured for over 100 years. They continue to be readily available and may provide a nearly optimized solution for many applications with respect to minimizing the reaction force or acceleration within a dynamic system. However, many types of specialized dampers are also available that deviate substantially from this linear relationship. It is then difficult to categorize the amount of damping in terms of percentage of critical damping since the amount of damping is constantly changing as the system moves. Non-linear damping components have substantial benefits in many dynamic systems. It is therefore imperative that these components are well known by those that are attempting to optimize the performance of a dynamic system subjected to shock and vibration environments.

Another kind of non-linear damper is one that varies its output force as a function of position. For example, a metering tube fluid damper uses a piston that progressively covers a series of orifice ports, thereby reducing the orifice area as the stroke increases. This results in a progressively higher damping coefficient as the damper strokes forward.

Yet another type of damper is one that can react or adapt its output function as a function of velocity or even acceleration. This type of damper can prove beneficial when being subjected to a variety of shock and vibration levels. For example, a vehicle that is required to provide an adequate suspension system for both on and off road conditions can benefit from an adaptive damper.

Types of Dampers

The following is a list of dampers that exist for use in control of dynamic systems that have proven effective for many applications:

Structural Damping – Structural damping is generally considered the amount of damping that is inherent in a structure and/or its materials. Structural damping levels are relatively low. However, its magnitude varies widely depending on the types of materials used and the design of the structure. The amount of critical damping, also known as the damping ratio, that exists in structures can be .5% of critical (damping ratio = .005) or less for rigid structures and can be as high as 10% (damping ratio = .10) for massive structures using lightweight construction and complex joints.

Coulomb or Frictional Dampers – Coulomb damping is often obtained by slippage of a joint at stress levels below that of the material yield strength. A wide range of damping ratios can be obtained, although the amount is generally limited by the frictional coefficients of the materials and the high amount of wear that can be experienced by high normal forces. Since friction is inherently high, this type of damping often leaves a permanent drift, or offset, from the original position of the system. The damping level will vary somewhat with temperature, wear, corrosion, aging, and exposure to external influences, such as water or oil.

Elastomer Dampers – Elastomers have the ability to provide both spring force (position dependent) and damping force (velocity and/or frequency dependent). Damping levels vary greatly depending on the compound type. Most elastomer dampers are highly non-linear. Care must be exercised in the design of elastomer dampers since they are temperature sensitive, they degrade with age and exposure to chemical reagents or UV light, and they are difficult to control to a high level of accuracy and consistency. However, they are generally inexpensive and standardized to some degree, making them readily available.

Active Dampers – Active dampers are those that are comprised of a power source, programmed control logic, an input measuring device, and a mechanical driver that has the ability to respond quickly to the input according to the logic and drive itself to reduce the response acceleration of the protected mass. Since the active damper has the ability to react to the input on a real time basis, active controls have the ability to provide added benefits over a completely passive damper in some instances.

However, the benefits come at a price that is often substantial. Active dampers (or active isolation systems) must possess a power source that is capable of reacting quickly the input. This requires a relatively high power source in most practical applications that consider the use of active dampers. Therefore, the weight, size and expense are difficult to overcome. Additionally, the complexity and reliability of active drivers are major factors when considering the appropriate applicability of active systems to solve a shock and vibration problem. Careful consideration must also be given to the level of improvement that can be realized through the use of active systems as opposed to passive or adaptive systems. Research has shown that only a limited amount of performance improvement, if any, can be realized with active dampers as compared to specialized passive or adaptive dampers.

Hydraulic (Fluid) or Viscous Dampers – Fluid or viscous dampers fundamentally obey the following equation:

$$F \text{ (force)} = C \times V^{\alpha} \tag{8}$$

where V is velocity, C is the damping constant, and α is the damping exponent. Dampers are available that can produce an exponent between approximately .2 and 2. Typically, fluid dampers with very low exponents near .2 produce this relationship through the use of pressure responsive valves (PRV's). Dampers with exponents near 2 typically obey this relationship due to the fact that the orifice type and the damping fluid is mainly governed by Bernoulli's equation of fluid flow that states that fluid pressure is a function of flow velocity squared (V^2) and the density of the fluid. As stated previously, dampers with an exponent of 1 are considered linear dampers.

Tuned Mass Dampers – Although not a new concept, tuned mass dampers (TMD's) have gained increased acceptance in a wide array of applications, especially for use in structural control, over the last several years. Tuned mass dampers are basically comprised of a suspended tuned mass and an inherent damping component set to control motion of the tuned mass. The natural frequency of that tuned mass is set to be at or near the response frequency of the structure. This arrangement ensures that the motion of the structure will be one-half cycle out of phase with the structure to effectively minimize or mitigate the gross motion of that structure.

A major advantage of a TMD is that it can provide damping to a complete structure by locating it in a discrete location. The main limitation is that it provides only a limited amount of added damping to a structure depending on the mass ratio of the TMD mass to the structure's effective mass. Figure 3 below illustrates the relationship between this mass ratio and the level of added damping provided in terms of percent of critical damping as previously defined, and the frequency ratio between the tuned mass and the natural frequency of the structure. For example, implementing a tuned mass that possesses 5% of the effective mass of the entire structure will provide only a maximum of 6% of critical damping. This needs to be considered when it is entirely possible to provide damping levels of 30% or more with traditional damping elements distributed within the structure.

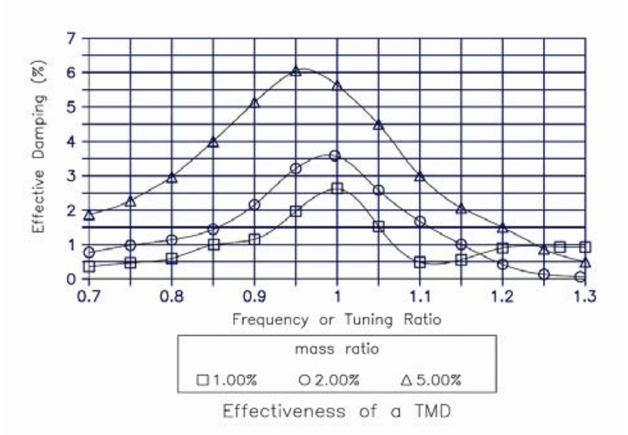

Figure 3

SHOCK / ENERGY ABSORBERS

The definition of a shock absorber is not absolute. It generally depends on the intended function of the device. Many components that are designed to minimize the force or acceleration into a protected mass are referred to as shock absorbers or snubbers. However, they are often designed to achieve the result of an isolator as described above. That is, they are intended to de-couple (or isolate) to some degree the input energy from a protected mass or structure. In achieving that function in an optimized fashion, they are often designed to produce small reaction forces, thereby reducing the acceleration to the protected mass accordingly, while still properly supporting the mass and returning it to its initial position. For example, shock absorbers in automobiles are designed to provide a maximum level of occupant comfort while preventing the suspension from bottoming over a wide range of input conditions. This is a balance between minimizing the reaction force and absorbing an adequate amount of kinetic energy for all conditions. Considering that intended function, shock absorbers can be considered to be shock isolators since they effectively de-couple the input energy from the protected mass.

Shock/energy absorbers are sometimes equivalent to shock isolators, but they generally differ in their intended function. For example, if a fixed amount of kinetic energy is already present in a moving mass that requires protection, a shock absorber would be designed to absorb that entire amount of energy, while again minimizing the forces to the mass. Simple physics for this application suggests that the most efficient shock absorber is one that reacts quickly to provide a constant force over its entire stroke (deflection) for a given input energy. Since energy is the summation of force times deflection, a maximum amount of energy is absorbed with a "square curve". A shock absorber with a perfectly square curve output function is considered 100% efficient. In reality, most shock absorbers need a small amount of time or deflection to build and relieve their output force, resulting in a departure from 100% efficiency. The most efficient shock absorbers are those that build their force quickly, hold that force constant with deflection, and relieve that force quickly near the end of stroke.

For a dynamic system with varying velocity input, an absorber that varies its force as a function of velocity squared, but holds its force constant over its stroke, is oftentimes desired. This is because the force output varies at the same rate that the energy level varies. See Equation 9 below. The challenge to providing that type of absorber is that even though the reaction force is a function of velocity squared, it needs to retain that force as the velocity (energy) is degrading with increasing stroke. This implies an absorber that varies with velocity and stroke at the same time. This type of absorber is available.

$$\text{Kinetic Energy} = \tfrac{1}{2} \times \text{mass} \times \text{velocity}^2 \qquad (9)$$

Figures 4 and 5 are graphical representations of the force versus deflection output of certain shock absorbers. Figure 4 illustrates the fact that a shock absorber with 100% efficiency (ideal constant force) is twice that efficient of a linear spring. Figure 5 illustrates an actual reaction curve of a shock absorber possessing a relatively high degree of efficiency.

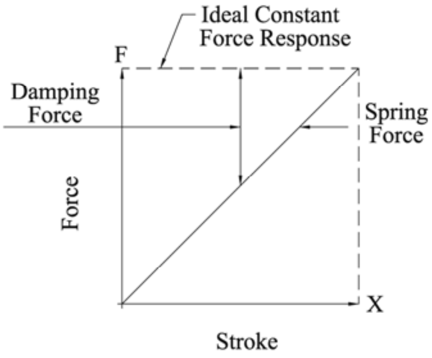

Figure 4

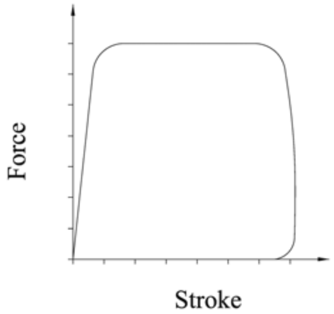

Figure 5

OPTIMIZATION OF SHOCK AND VIBRATION ISOLATORS

As outlined above, hardware that is designed to mitigate shock, vibration, or some form of kinetic energy contain numerous types of attributes that need to be matched and optimized to their particular application. Some optimization techniques are simple while others are complex. As with many dynamic systems under evaluation for shock and/or vibration response and mitigation, it is oftentimes necessary to break down the effort into three main phases: The first is to define and fully understand the dynamic environment that exists. The second is to define the fragility level of the equipment. The last is to determine whether or not mitigation through isolation or other means is necessary. Additionally, this final phase requires that the isolation system parameters be defined through analysis or test as necessary. This analysis is sometimes simple and can be handled through proven algorithms and techniques. Other times, a complex computer model and an iterative optimization process are necessary.

Determining the fragility level of the protected mass is a key consideration when implementing shock and vibration mitigating hardware. Many times, reducing the peak acceleration becomes the goal. Other times, reducing the motion, velocity, or change in acceleration (jerk) is more appropriate to reduce to a determined level. In the field of bio-dynamics, other parameters such as cumulative shock or vibration indices are minimized.

In any case, it is imperative that the analyst consider the input, the proper response parameters to target, and to be aware of the tools that exist to solve these problems.

CONCLUSIONS

1. Isolation, damping systems, and shock absorbers are very useful tools in solving problems relating to shock and vibration environments.

2. These are complex tools and no comprehensive manuals exist for their optimal use. A close relationship with isolation hardware suppliers should be established for proper use of this technology.

3. It is essential that analysts and systems engineers be equipped with a full database of isolation system attributes that have proven effective and reliable in a wide variety of shock and vibration isolation applications in the past. This paper has presented many of those attributes.