1.0 FUNDAMENTALS OF VIBRATION AND SHOCK

1.1 What Is Vibration?

Mechanical vibration is a form of oscillatory motion. It occurs in all forms of machinery and equipment. It is what you feel when you put your hand on the hood of a car, the engine of which is running, or on the base of an electric motor when the motor is running. Perhaps the simplest illustration of a mechanical vibration is a vertical spring loaded with weight (W), as shown in Figure 1. In this position, the deflection of the spring from its free state is just sufficient to counterbalance the weight W. This deflection is called the *STATIC DEFLECTION* of the spring. The position in which the spring is at rest is No. 1. The spring is then slowly extended to position No. 2 and released. The elastic force moves the block W upward, accelerating up to the mean position and then decelerating moving further up. The uppermost position of the weight (position No. 3) is at the same distance from position No. 1 as position No. 2, but in the opposite direction. The subsequent motion of the weight as a function of time, if there is only negligible resistance to the motion, is repetitive and wavy if plotted on a time scale as shown by line 1 in the graph. This simple model exhibits many of the basic characteristics of mechanical vibrations. The maximum displacement from the rest or mean position is called the *AMPLITUDE* of the vibration. The vibratory motion repeats itself at regular intervals (A_1, A_2, A_3). The interval of time within which the motion sequence repeats itself is called a *CYCLE* or *PERIOD*. The number of cycles executed in a unit time (for example, during one second or during one minute), is known as the *FREQUENCY*. The *UNITS OF FREQUENCY* are 1 cycle/sec or 1 Hertz (Hz) which is standard. However, "cycles per minute" (cpm) are also used, especially for isolation of objects with rotating components (rotors) which often produce one excitation cycle per revolution which can be conveniently measured in cpm. When, as in Figure 1, the spring-weight system is not driven by an outside source, the vibration is a *FREE VIBRATION* and the frequency is called the *NATURAL FREQUENCY* of the system, since it is determined only by its parameters (stiffness of the spring and weight of the block).

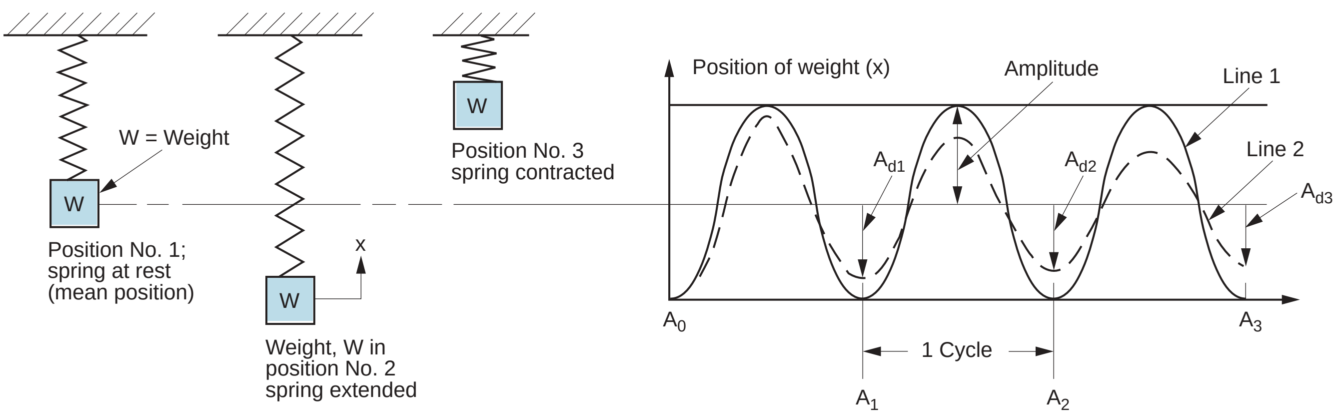

Figure 1 Free Vibrations of a Simple Vibratory System

In general, vibratory motion may or may not be repetitive and its outline as a function of time may be simple or complex. Typical vibrations, which are repetitive and continuous, are those of the base or housing of an electric motor, a household fan, a vacuum cleaner, and a sewing machine, for example. Vibrations of short duration and variable intensity are frequently initiated by a sudden impulsive (shock) load; for example, rocket upon takeoff, equipment subject to impact and drop tests, a package falling from a height, or bouncing of a freight car. In many machines, the vibration is not part of its regular or intended operation and function, but rather it cannot be avoided. Vibration isolation is one of the ways to control this unwanted vibration so that its adverse effects are kept within acceptable limits.

1.1.1 Damping

The vibratory motion as a function of time as shown in Figure 1 (line 1) does not change or fade. The elastic (potential) energy of the spring transforms into motion (kinetic) energy of the massive block and back into potential energy of the spring, and so on. In reality, there are always some losses of the energy (usually, into thermal energy) due to friction, imperfections of the spring material, etc. As a result, the total energy supporting the vibratory motion in the system is gradually decreasing (dissipated), thus diminishing the intensity (amplitude) of the spring excursions, as shown by line 2 in Figure 1 ("decaying vibration"). This phenomenon is called *DAMPING*, and energy-dissipating components are called *DAMPERS*, Figure 2. The rate of decay of amplitude in a system with damping is often characterized by *LOGARITHMIC* (or *LOG*) *DECREMENT* δ defined as

$$\delta = \log (A_n/A_{n-1}), \qquad (1)$$

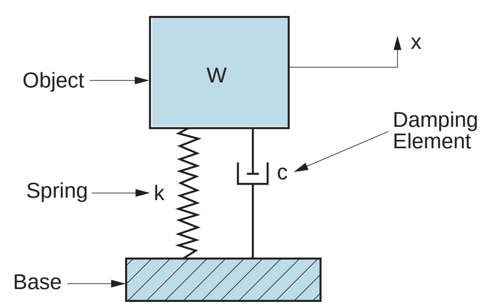

Figure 2 Simple Vibratory System with Damping

where A_n and A_{n-1} are two sequential amplitudes of the vibratory process. In many cases δ can be assumed constant during the decaying vibratory process. Although the cycles of the damped motion as shown by line 2 in Figure 1 are not fully repetitive, the number of cycles in a unit of time is still called *FREQUENCY.*

1.2 What Is Shock?

Shock is defined as a *TRANSIENT* condition whereby kinetic energy is transferred to a system in a period of time which is short, relative to the natural period of oscillation of the system. Shock usually contains a single impulse of energy of short duration and large intensity which results in a sudden change in velocity of the system undergoing shock. The principles involved in both vibration and shock isolation are similar. However, differences exist due to the steady-state nature of vibration and the transient nature of shock. Shock may occur in an infinite variety of ways and can be very complex. The simplest form is a single impulse of extremely short duration and large magnitude. Figure 3 [5] shows the most commonly employed pulse shapes used in test specifications.

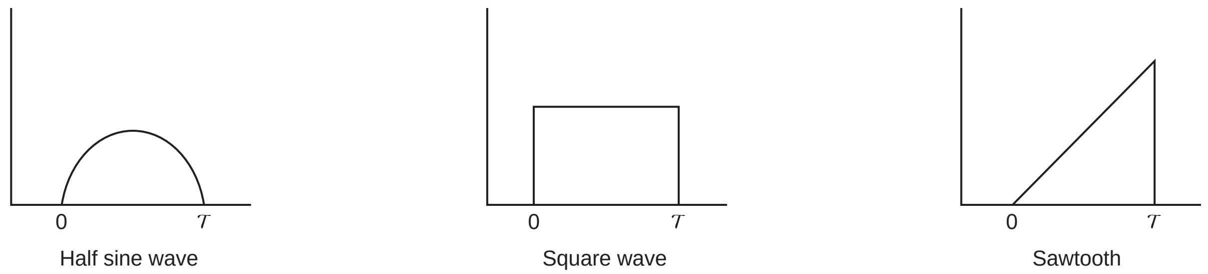

Figure 3 Basic Pulse Shapes

The reduction in shock severity, which may be obtained by the use of isolators, results from the storage of the shock energy within the isolators and its subsequent release into a "smoother" vibratory process, over a longer period of time (at the natural frequency of the spring-mass system) and/or from dissipation of the shock energy (its transformation into thermal energy). However, the energy storage can only take place by a generally large deflection of the isolator.

Inasmuch as a shock pulse may contain frequency components ranging from very low to very high, it is not possible to avoid excitation of vibratory process of the isolator/mass system with its natural frequency. On the other hand, if the duration of the shock pulse is short, the response of the system may not have serious consequences. Figure 4 [5] demonstrates the comparative response of a spring mass system to a rectangular pulse whose duration is greater than the natural period of the vibratory system (I) and to a relatively short impulsive-type shock (II).

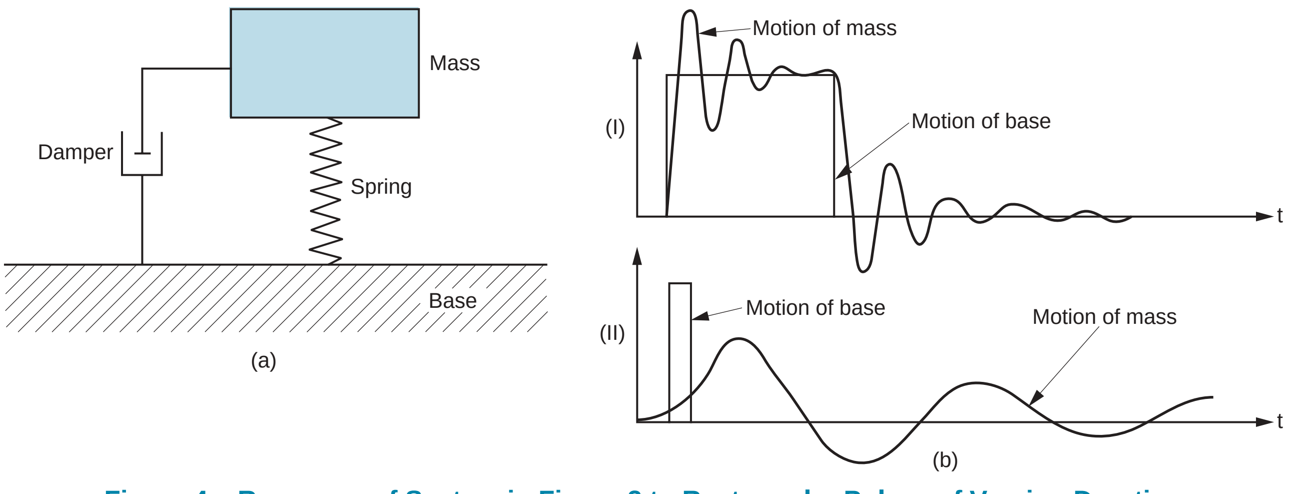

Figure 4 Response of System in Figure 2 to Rectangular Pulses of Varying Duration

1.3 What Is Noise?

Sound is a vibration of air. The air in this case is an elastic member. The vibrations of the air have a frequency and an intensity (loudness). The frequency can be expressed in cycles per second or cycles per minute. The audible frequencies range from about 20 Hz to about 18,000 Hz, although some human ears are more sensitive and may have a somewhat broader range. Some sounds are desirable and pleasant for some people, such as music. Unwanted/objectionable sounds represent *NOISE.* Intensity or loudness of noise is measured in decibels (dB). The decibel is a measure of the sound pressure in relation to a standard or reference sound (.0002 microbars, which is the threshold of hearing for sounds for many people). The sound/noise loudness in dB is equal to 20 times the common logarithm of this ratio. Typical values of sound pressure level in dB are shown in Tables 1a and 1b.

Table 1a: SOUND PRESSURE LEVELS (SPL) FROM TYPICAL NOISE SOURCES

SPL dB	Effect	Source
180	Impairs Hearing	Rocket engines
160	Impairs Hearing	Jet aircraft engines
140	Pain	Jet aircraft engine
120	Threshold of pain	Thunder, artillery
110	Deafening	Nearby riveter, elevated train
100		Boiler factory, loud street noise
90	Very Loud	Noisy factory, unmuffled truck
80		Police whistle, noisy office
70	Loud	Average street noise, average radio
60		Average factory, noisy home
50	Moderate	Average coversation, average office
40		Quiet radio, quiet home or private office
30	Faint	Average auditorium, quiet conversation
20		Rustle of leaves, whisper
10	Very Faint	Soundproof room
0		Threshold of hearing

From: *Marks' Standard Handbook for Mechanical Engineers*, Sixth Edition, McGraw Hill Book Co. Inc. New York, 1958, Section 12, p. 153; and "How to Specify Audible Noise" by E.A. Harris and W.E. Levine, *Machine Design* Nov. 9, 1961, p. 168.

Various industrial operations and related noise levels recorded at distances of from one to three feet from machine. **

Table 1b: VALUES OF SOUND AND NOISE INTENSITY

Machine	Overall Sound Pressure Level
Grinder (portable)	90-100 decibels
Drop hammer	100-105 decibels
Lathes	80-90 decibels
Punch press	95-105 decibels
Riveting guns	95-105 decibels
Sander (portable)	80-95 decibels
Screw machine	90-100 decibels
Sewing machines	90-100 decibels
Wood saw	95-100 decibels

** From: "Acoustical Enclosures Muffle Plant Noise" by S. Wasserman and A. Oppenheim, *Plant Engineering*, January 1965

1.4 Principles of Vibration Isolation

In discussing vibration isolation, it is useful to identify the three basic elements of all vibrating systems: the *object to be isolated* (equipment unit, machine, motor, instrument, etc.); the *isolation system* (resilient isolation mounts or isolators); and the *base* (floor, base plate, concrete foundation, etc). The isolators (rubber pads, springs, etc.), are interposed between the object and the base. They are usually much smaller than the object and the base.

If the object is the source of vibration, the purpose of vibration isolation is to *reduce the force* transmitted from the object to the base.

If the base is the source of vibration, the purpose of isolation is to *reduce the vibratory motion* transmitted from the base to the object, so that vibratory displacements in the work zone (between the tool and the part in a precision machine tool, the measuring stylus and the measured part in a coordinate measuring machine, the object and the lens in a microscope, etc.) do not exceed the allowable amounts. That is, probably, the most common case (protecting delicate measuring instruments and precision production equipment from floor vibrations, transportation of vibration-sensitive equipment, etc.).

In both cases, the principle of vibration isolation is the same. The isolators are resilient elements. They act as a time delay and as a source of temporary energy storage, which evens out the force or motion disturbance on one side of the vibration mounts and transmits, if properly selected, a lesser disturbance to the other end (to the base in case of force isolation, to the object in case of motion isolation).

A judicious design of the vibration isolation system insures that this effect is achieved. Conversely, a **poorly designed isolation system**, not having proper frequency characteristics, **can be worse than no isolation at all.**

In addition to its function as a time delay and source of temporary energy storage, vibration mounts can also function as energy dissipators or absorbers. This effect is usually produced by the damping characteristics of materials, viscous fluids, sliding friction, and dashpots, although in general these may or may not be part of the isolator. The damping, or energy-dissipating effect of an isolator may be negligible or substantial depending on the application. The main purpose of isolator damping is to reduce or to *attenuate* the vibrations as rapidly as possible. Damping is particularly important at certain frequencies which cause RESONANCE. This occurs when the natural frequency of the object on isolators comes close to the vibration frequency of the source. For example, if an electric motor runs at 3600 rpm, then the object-isolator natural frequency of 3600 cycles per minute (60 Hz) corresponds to the resonance condition. If a machine operates near resonance, or has to pass through a resonant speed in order to attain the operating speed, damping is important in alleviation of the vibration buildup.

In summary, a good vibration mount functions as a time delay, temporary energy absorber and to some extent as an energy dissipator, or damper. The engineering design of a vibration mount consists in identifying the characteristics of the source of the vibration, the mechanical characteristics of the equipment and the determination of the mount characteristics, in order to achieve a specified degree of vibration reduction.

1.5 Principles of Noise Reduction

A good vibration isolation system is reducing vibration transmission through structures and thus, radiation of these vibration into air, thereby reducing noise.

There are many ways to reduce noise. One of the most practical and effective may be the use of vibration mounts. As a general rule, a well-designed vibration isolator will also help reduce noise. In the case of panel flutter, for example, a well-designed vibration mount could reduce or eliminate the noise. This can be achieved by eliminating the flutter of the panel itself, or by preventing its transmission to ground, or by a combination of the two. The range of audible frequencies is so high that the natural frequencies of a vibration mount can usually be designed to be well below the noise-producing frequency.

In order to reduce noise, try to identify its sources; e.g., transformer hum, panel flutter, gear tooth engagement, rotor unbalance, etc. Next, identify the noise frequencies. Vibration isolators for these sources designed in accordance with the guidelines for vibration and shock control may then act as barriers either in not conducting the sound, or in attenuating the vibration which is the source of the noise.

2.0 BASIC DEFINITIONS AND CONCEPTS IN VIBRATION AND SHOCK ANALYSIS

2.1 Kinematic Characteristics

COORDINATE — A quantity, such as a length or an angle, which defines the position of a moving part. In Figure 1, x is a coordinate, which defines the position of the weight, W.

DISPLACEMENT — A change in position. It is a vector measured relative to a specified position, or frame of reference. The change in x (Figure 1) measured upward, say, from the bottom position, is a displacement. A displacement can be positive or negative, depending on the sign convention, translational or rotational. For example, an upward displacement may be positive, and a downward displacement negative. Similarly, a clockwise rotation may be positive and a counterclockwise rotation negative. Units: inches, feet, meters (m), millimeters (mm), or, in the case of rotations: degrees, radians, etc.

VELOCITY — The rate of change of displacement. Units: in/sec, mph., m/sec, etc. Velocity is a vector whose magnitude is the *SPEED*. Angular velocity might be measured in radians/sec or deg/sec, clockwise or counterclockwise.

ACCELERATION — The rate of change of velocity. Units: in/sec^2, m/sec^2, etc. It is a vector and has a magnitude and direction. Angular acceleration might be measured in rad/sec^2 or deg/sec^2, clockwise or counterclockwise.

VIBRATORY MOTION — An oscillating motion; such as, that of the weight W, in Figure 1.

SIMPLE VIBRATORY MOTION — A form of vibratory motion, which as a function of the time is of the form $x = a \sin \omega t$, where a and ω are constants. The maximum displacement, a, from the mean position (x = 0) is the *AMPLITUDE*; the *FREQUENCY* (rate at which the motion repeats itself) is $f = \omega/2\pi$ cycles/sec, where *ANGULAR FREQUENCY* ω has the dimensions of rad/sec, and frequency f has the dimensions of reciprocal time; e.g. reciprocal seconds 1/sec. Such motion is also called harmonic or sinusoidal motion.

PERIOD, CYCLE — The interval of time within which the motion repeats itself. In Figure 5, this is T seconds. The term cycle tends to refer also to the sequence of events within one period.

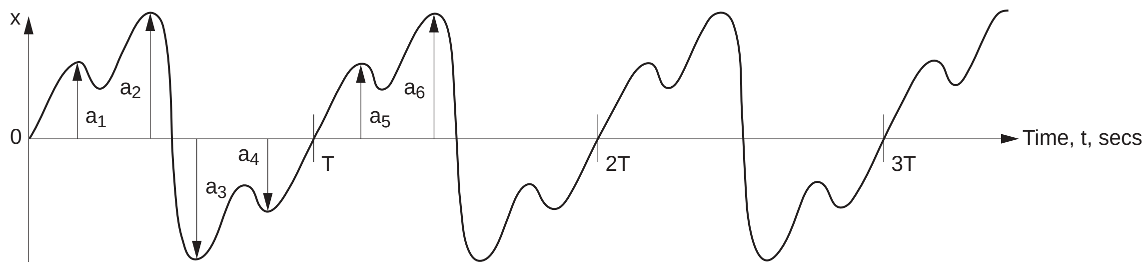

Figure 5 Periodic Motion

AMPLITUDE — Figure 5 shows time history of a vibratory motion, which repeats itself every T seconds. The maximum values of the displacement, x, from the reference position (x = 0) are called PEAKS. These are (a_1, a_2...). The largest of these is called the *PEAK AMPLITUDE.*

STEADY-STATE MOTION — A periodic motion of a mechanical system; e.g., a continuously swinging pendulum of constant amplitude.

STOCHASTIC or RANDOM MOTION — A motion which changes with time in a nonperiodic, possibly very complex, manner.