A BRIEF INTRODUCTION TO TERMINOLOGY AND BASIC THEORY

What is Vibration?

A body is said to vibrate when it describes an oscillating or 'to and fro' motion about a reference position. Oscillations are mainly caused by internal or externally applied forces and/or moments produced (mechanically) by rotating and/or reciprocating masses or by equipment utilizing varying electrical and magnetic fields.

Vibration is characterised by both its magnitude and frequency. It can occur at a single frequency e.g. a tuning fork or at several frequencies as in the case of an internal combustion engine.

In mechanical systems the magnitude or amplitude of vibration can be expressed in units of displacement, velocity or acceleration and as peak, r.m.s or peak to peak values.
The RMS amplitude is most descriptive giving a value which is a measure of the energy content and hence the destructive potential of the vibration.

The number of oscillations occuring per second is called the frequency of vibration and is measured in Hertz. Calculations often use a frequency expressed in radians/second, where $2 \times \pi = 6.283185$ radians/second is equivalent to1Hertz (Hz).
E.g. 600 cycles per minute = 10 oscillations per second = 10Hz = $2 \times \pi \times 10$, i.e. 62.83185 radians/second. The angular representation derives from the fact that a periodic vibration can be represented as the vector sum of a series of sine waves.

What are the effects of Vibration?

On the negative side vibration can damage machinery, structures and the environment. It can produce unwanted noise and create unhealthy work, travelling or living environments.

On the positive side vibration can provide a necessary part of a manufacturing or construction process as in construction plant, breakers, tamping machines and vibratory screens.

What is a vibration isolator or anti-vibration mounting (AVM) and why use them?

A vibration isolator or anti-vibration mounting AVM) is generally a load carrying, spring-like element with some degree of damping built-in.
By supporting equipment or machines on vibration isolators (Anti-vibration mountings), it is possible to reduce the magnitude of the vibration forces or moments that are actually transmitted to the support structure.

Vibration isolators can also be used to protect sensitive equipment from the influences of externally generated vibration (motion), present in supporting structure.

By using AVM's, it is possible to improve local environments within factories, offices, hospitals and the home etc. and in mobile environments including trains, boats, planes and other forms of transportation etc., although in mobile applications additional provision must be made to restrict shock movements.

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How does an AVM work?

*The terminology **anti-vibration mounting** although used widely misrepresents the way in which an AVM works. It does not stop or control vibration but permits oscillation of the suspended equipment or the support structure whilst reducing the forces transmitted.*

All machines with rotating and reciprocating parts create vibration by their nature of operation. A machine fixed solidly onto a support structure transmits all vibration forces directly into the structure.

Consider such a vibrating machine and the options to fix it in position:

If the machine is first rigidly attached to a rigid support structure, it is then not free to move under the influence of its vibratory forces and as a consequence all forces are transmitted undiminished into the support structure.

Imagine the other extreme where the machine is floated in space above the structure, it is now free to respond to its internally generated vibration forces and will oscillate (move) in space in response to these forces. The amplitude of vibration is mass controlled. For example, adding mass to the machine will reduce the vibration amplitude, removing mass increase the amplitude. Without attachments to the structure, the forces transmitted will be zero.

Between these extremes, using **suitably selected AVMs**, it is possible to allow the machine mass to vibrate almost freely whilst achieving a reduction of the forces transmitted to the support structure to values less than those generated by the machine.

AVMs can also protect equipment from external vibration due effectively to this ability to accommodate movement. The softer the AVM spring the lower the force transmitted for a given movement.

BUT BEWARE: An AVM is only as effective as the full system design and is not in itself the solution!!!

What are the factors effecting performance that must be considered when selecting AVMs?

Can the vibration effects be reduced?

YES: By adding mass to the machine and foundation it is possible to reduce vibration amplitudes, but this does **not reduce the forces involved.**

YES: By fine balancing of the rotating and reciprocating masses the vibratory excitation forces and moments can often be reduced, but it can be expensive and frequently impractical.

YES: **To varying degrees of performance** by using AVM’s.

Stiffness and capacities of AVM’s vary widely so it is important to establish the preferred characteristics for any system.

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AVMs that are available in the market place can vary noticeably in performance and so to identify the preferred choice, it is necessary to look at the dynamics involved. This is most simply explained using a single degree of freedom model.

Imagine the equipment as a simple mass supported on a simple spring-like element.
N.B. All materials move or deflect when a force or moment is applied. In the case of an AVM the amount of movement (or deflection as it is often termed) will be influenced by the size of the applied force and the shape, form, size, material and type of the AVM. The force required per unit of deflection is called the stiffness and is frequently expressed in units of Newtons/metre, N/mm or kN/m.

By mathematically modelling the mass ‘m’ in kilograms (kg), supported on the spring of stiffness ‘k’ (N/m) and applying Newton’s laws, a second order differential equation containing a forcing (excitation) function, a mass and acceleration term, a viscous damping and velocity term plus a constant can be derived.

Initially by ignoring damping effects and setting the external excitation to zero, the system has a defined solution when:

$$F_n = \frac{1}{2\pi}\sqrt{(k/m)}$$

Where F_n is a frequency of oscillation and represents a characteristic of the system that is a function of only the mass and the spring dynamic stiffness. It is called the undamped natural frequency of the system.

The natural frequency of the system is the frequency of oscillation that occurs when, with no other excitations applied, the system is displaced from the static equilibrium position and released.

N.B. In all cases the stiffness in the equation above refers to the dynamic stiffness. AVMs are produced in many materials and some like rubber exhibit different stiffness characteristics depending on the rate at which load is applied and the amplitude of the cyclic loading. In these cases the ‘k’ stiffness term in the above equation is greater than the tangent to the load versus deflection (Static stiffness) curve. In steel spring type AVMs the dynamic stiffness is virtually identical to the static.

When the general equation is solved including damping, the natural frequency formulae is modified to include a damping term, however in most AVM’s, damping is normally quite small and consequently, the non-damped formulae provides accurate agreement for most standard AVM’s.
For systems using heavily damped AVMs, the natural frequency reduces as the level of damping increases.

What is the significance of the natural frequency?

Solving the full equation with damping terms and excitation function produces a general solution containing transient and steady state solutions.
The transient solution decays under the influence of the damping present in the mountings and the system settles into a steady vibratory state, oscillating at the forcing frequency.

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The magnitude of the transmitted force can be shown to be dependent on the magnitude of the applied force, the damping and the ratio of excitation frequency to natural frequency. For the steady state solution, the ratio of transmitted force to applied force is termed the transmissibility. This ratio can be plotted as a generalized curve in terms of the ratio of excitation frequency to the system natural frequency, over a frequency range.

By varying the amounts of damping a series of general curves can also be obtained.

What the mathematics show is that for an excitation frequency less than the natural frequency, the transmitted force to the structure is greater than if the mass were fixed solidly.
As the excitation frequency increases, approaching the natural frequency, the amplitude of vibration of the mass and the transmitted force both increase, reaching maximum values at the natural frequency. Any system vibrating at its natural frequency can be said to be in resonance.

The level of damping present in a mounting system dictates the maximum response amplitude reached, when subject to continuous excitation at and around the resonant frequency.
As the excitation frequency increases above the natural frequency it reaches a point 1.414 times the undamped natural frequency where the transmitted force is exactly equal to the applied force.
Above this 1.414 times natural frequency, the transmitted force starts to reduce and continues to reduce with increasing frequency.

To achieve any isolation, or reduction of the applied forces*, it is therefore necessary to design an AVM support system to* ***ensure the excitation frequency is greater than 1.414 times the natural frequency. The greater this ratio, the better the isolation performance of the system.***
All installations are designed to work using this principle and many systems are designed with ratios greater than 3.

Damping

To this point, the term damping has not been explained.
All AVM mountings possess some level or degree of damping, the amount depending on the material and type of mounting construction. In simple terms, the amount of damping determines the rate at which energy is removed from the system, which effectively determines the maximum amplitude that is achieved at resonance. In heavily damped systems, the damping affects the natural frequency and can if high enough, prevent oscillation. A critically damped system is one which, when displaced from equilibrium, returns to its' equilibrium position in the shortest possible time without performing an oscillation. For most practical AVM systems the amount of damping is small and the vertical natural frequency can be calculated accurately knowing only the equipment mass and the AVMs vertical dynamic stiffness.

N.B. All AVM's exhibit stiffness properties that are generally characterised in three mutually perpendicular directions.
A basic installation will consist of a piece of equipment, typically supported on four or more flexible elements or AVMs. Forces and moments applied to the equipment can produce linear movements of the equipment along three mutually perpendicular axes and rotations around these three axes. The system is said to possess six degrees of freedom.

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All single bodies mounted on AVMs have six degrees of freedom and hence six natural frequencies.

Complex installations can have systems where an upper mass sits on AVM's on top of a second mass which itself is supported on AVM's. This is a two mass twelve degrees of freedom system and requires careful design and consideration of all external factors. Similarly for critical single mass systems, to achieve optimum performance it is necessary to consider all six degrees of freedom when designing the isolation system.

Vibracoustics will undertake or assist on these more complex installation designs as required, however, experience has shown that in many practical applications, by applying certain guidelines and considering only the vertical direction, it is possible to design an acceptable AVM system.

Can selection be simplified?

Yes!

Consider a mass '**m**' supported on a linear mounting of spring stiffness '**k**',

In static equilibrium under the influence of gravity '**g**', the deflection '**d**' in the spring is given by equating the forces:

$$m \times g = k \times d,$$

which can be rewritten as $g/d = k/m$,

and by replacing **k/m** in $F_n = \frac{1}{2\pi}\sqrt{(k/m)}$,

the natural frequency reduces to $F_n = \frac{1}{2\pi}\sqrt{(g/d)}$

where '**g**' is nominally a constant equal to 9.81m/sec^2

The vertical natural frequency of a mounting system is therefore proportional to:

$$\sqrt{(1/d)}$$

the vertical mounting deflection of the AVM due to the supported mass.

Using this formulea, AVM selection is simplified to establishing that sufficient vertical deflection is achieved, under the applied mounting static load.

Note:
For most AVM's the Dynamic stiffness which actually determines the natural frequency, is greater than the Static stiffness and generally the harder the compound, the greater the Dynamic to Static stiffness ratio. To ensure adequate isolation is achieved therefore, deflections larger than required to achieve minimum isolation are chosen to allow for the dynamic stiffening of the AVM. This dynamic to static adjustment is covered in 04_S_30_34.

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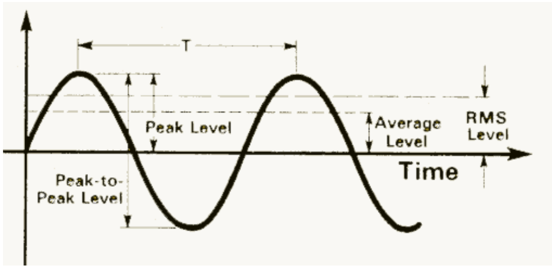
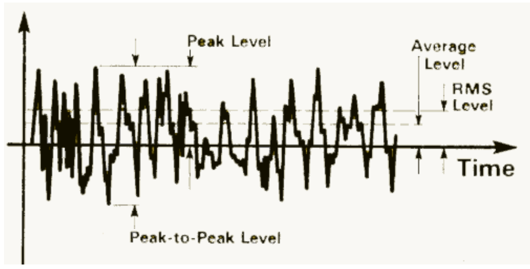
GLOSSARY

Acceleration:
Acceleration is a vector quantity that specifies the time rate of change of velocity.

Amplitude:
Amplitude is the maximum value of a sinusoidal quantity (i.e. acceleration, displacement).





Damping:
Damping is dissipation of energy with time or distance that in an oscillating system limits maximum amplitude at the system natural frequency.

Free Vibration:
Free vibration is the periodic motion occurring when an elastic system is displaced from its equilibrium position in the absence of forced excitation.

Frequency:
Frequency is the number of times the motion repeats itself per unit of time, where the unit of cycle per second is called Hertz (Hz.) and is equal to the reciprocal of the period.

Forced Vibration:
Forced vibration is the vibration resulting from the application of an external periodic force.

Foundation (Support):
A foundation is a structure that supports the gravity load of a mechanical system. It may be fixed in space, or it may undergo a motion that provides excitation of the supported system.

Isolation:
Isolation is effectively the reduction in the capacity of a system to respond to an excitation. This is achieved by the use of resilient supports.

Natural Frequency:
Natural Frequency is the frequency of free vibration. For a multi-degree of freedom system, the natural frequencies are the frequencies of the normal modes of vibration.

Periodic Motion:
Periodic motion is a motion that repeats itself at definite intervals of time.

Random Vibration:
Random vibration is vibration whose magnitude is not specified for any given instant of time.

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Resonance:

Resonance is the frequency match between the natural frequency of the system and the external forced vibration frequency and occurs at the particular frequency at which any change, however small, results in a reduction in the response of the system. In most systems large amplitudes will occur at resonance.

Resonant Frequency:
Resonant frequency is a frequency at which a resonance occurs.

Shock Absorber:
A shock absorber is a device which dissipates energy to modify the response of a mechanical system to an applied shock.

Shock Isolator (Mount):
A shock isolator is a resilient support that tends to isolate a system from a shock motion (excitation).

Spring Rate:
Force necessary to produce a unit deflection in an elastic element, usually given in units of N/m, N/mm and kN/m.

Steady State Vibration:
Steady state vibration exists in a system if the velocity of each particle is a continuing periodic quantity.

Transient Vibration:
Transient vibration is temporarily sustained vibration of a mechanical system. It may consist of forced vibration.

Transmissibility:
Transmissibility is the non-dimensional ratio of the response amplitude of a system in steady-state forced vibration to the excitation amplitude. The ratio may be one of forces, displacements, velocities or accelerations, frequently expressed as a percentage.

Velocity:
Velocity is a vector quantity that specifies the time rate of change of displacement with respect to a reference frame.

Vibration:
Vibration is the variation of the magnitude of a parameter (e.g. displacement, velocity etc.) of a mechanical system, usually with time, about some reference value, where the magnitude is alternatively greater than, then smaller than, the reference. To and fro motion about a position of equilibrium.

Vibration Isolator:
A resilient support that tends to isolate a mechanical system from foundation motion, or a supporting structure, from the steady state excitation produced within the mechanical system.

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