Vibration Isolation Theory of Foundations for Buildings, Equipment & Machines

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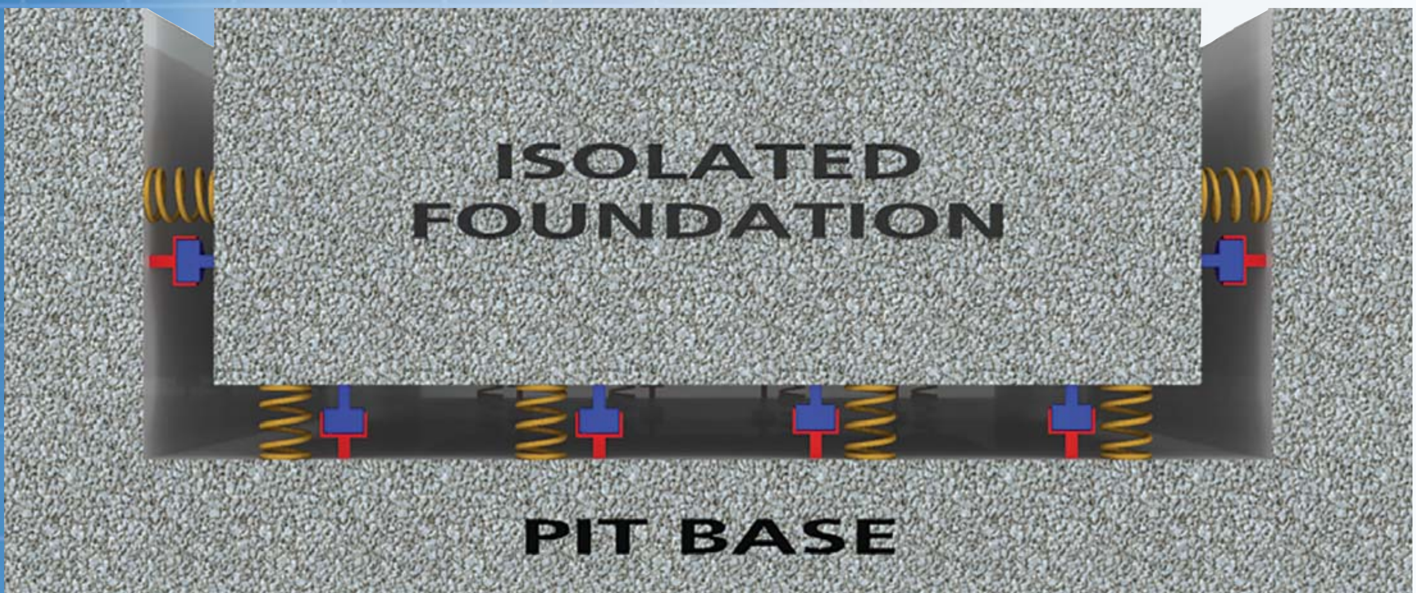
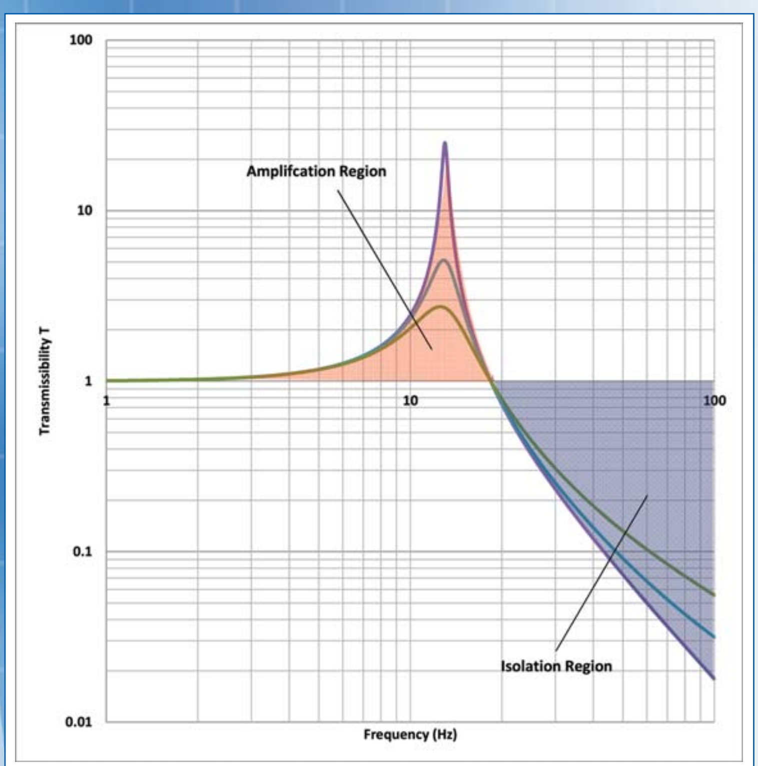




Vibration Isolation Theory of Foundations

for Buildings, Equipment & Machines

Introduction and Background

Vibrating, rotating, reciprocating and impacting equipment create machine-induced vibration and/or shock, which is transmitted into their support systems. Rotating machines and equipment that are not properly balanced produce centrifugal forces creating steady state and random vibration. Machines generating pulses or impacts, such as forging presses, injection molding, impact testers, hammers, centrifugal pumps and compressors are the most predominate sources of vibration and shock.

If the equipment requiring isolation is the source of unwanted vibration (Figure 1), then the purpose of isolation is to reduce the vibration transmitted from the source to its support structure. This vibration producing equipment consists mainly of machines that apply severe dynamic forces in their supporting structures.

Conversely, if the equipment requiring isolation is the recipient of unwanted vibration (Figure 2), then the purpose of isolation is to reduce the vibration transmitted from the support structure to the recipient to maintain performance. This includes equipment such as precision machine tools and measuring machines where vibrations must be kept within acceptable limits to achieve the desired surface finish, tolerances or accuracies.

Depending on the circumstances, it should be noted that a machine could be both a source *and* recipient of unwanted vibration. For example, a surface grinder is generally a vibration-sensitive piece of equipment that needs to be protected from floor vibrations. However, as the surface grinder reverses its heavy table during operation, it produces a large dynamic force, which may disturb other nearby precision equipment.

Some machine tools of ordinary precision are neither sensitive to vibration nor produce large dynamic forces, and therefore may or may not require isolation.

Operating frequencies of rotating/reciprocating machines often are very close to the natural frequency of their support structure (floor slab and soil). Compressors, for example, can generate vibration of substantial magnitudes at low frequencies that coincide with the natural frequency of the floor slab, thus creating a resonance (amplification of vibration) in the floor.

In order to achieve acceptable amplitudes of vibration at the source or recipient, it becomes necessary to make the support structure independent (isolated) from the rest of the environment. This separation prevents vibration from being transmitted directly through the support structure.

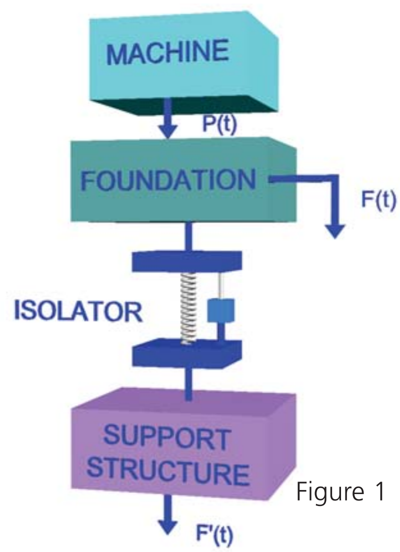


Figure 1

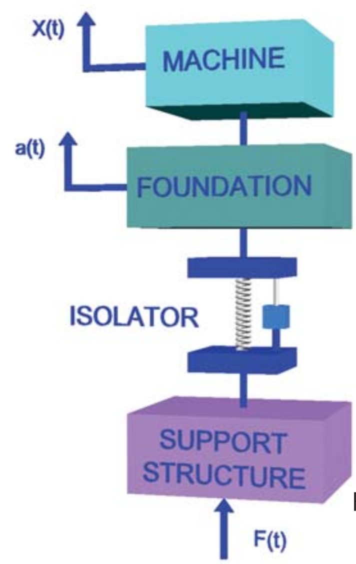


Figure 2

The separation method of cutting the existing floor slab or even creating trenches around machines to reduce the vibration being transmitted by the soil beneath the floor slab is experimental at best and often not a practical solution. A thorough understanding of the machine, the support structure (floor) and the soil is required. The effectiveness of this approach relies heavily on the soil mechanics, magnitude and frequency of the vibration amplitudes to be reduced. To be an effective solution, trenches and slab cuts can be up to 6 feet deep and 10 inches wide, which requires the soil to be extremely stable and can also cause safety issues.

Soil Mechanics

When installing machinery or equipment on a support foundation that rests directly on soil as the means of providing isolation, the soil conditions must be taken into account. Poorly designed and installed foundations may amplify vibration or worse, may settle unevenly and sink. Interaction between the soil and the foundation is equally as important as the interaction between the machine and the foundation.

Any static and dynamic forces exerted on the foundation also are exerted on the soil, and the load-bearing capacity of the soil is a key factor in determining the size of the foundation.

If soil alone is to be used as the means of isolation, it is necessary to know the characteristics of the energy dissipative properties of the soil. Establishing these properties depends not only on the type of soil, but also on the physical design of the foundation; in particular, the depth, the ratio between length and width and the material and density of the backfill.

It is difficult to take into account the influence of all these factors on the value of the energy dissipative properties of the soil. Therefore, the natural frequency and damping properties of the soil cannot be clearly defined based on the soil type alone. (Estimated values for soil natural frequency are listed in Table 1.)

Additionally, the natural frequency of soil can increase if the input vibration amplitudes are small and can decrease when the input vibration amplitudes are larger.

The damping property of most soils decreases as the pressure beneath the foundation increases and also when amplitudes of vibration are small. The larger the vibration input and the contact area of the foundation, the larger the damping value of the soil, and as a result, the lower the amplification of vibration at the soil's natural frequency.

Natural Frequencies of Soils*

Ground or Structure	Frequency (Hz)
Peat	7
Suspended concrete floor	10 - 15
Ground floor	12 - 34
Soft clay	12
Medium clay	15
Stiff clay	19
Loose fill	19
Dense medium grain sand	24
Very dense mixed grain sand	24
Uniform coarse sand	26
Pea gravel	28
Limestone	30
Hard sandstone	34

Table 1

*Assumes soil is homogeneous. Values do not account for amplitude of vibration input or foundation geometry.

The determination of a soil's dynamic properties (spring rate, damping) can be highly indeterminate. In many cases, the calculations are complex and many assumptions are made. Energy dissipation does occur in soil; however, the rate of damping and the natural frequency are a function of the magnitude of the vibration input and foundation geometry.

In many cases, manufacturing and quality control must co-exist in workcells or in close proximity to one another. For certain machines, the permissible amplitudes of machine foundation vibrations in a manufacturing environment are very low. It often is very difficult to decrease or isolate vibration amplitudes by properly selecting the contact area where the foundation meets the soil. It also may not be possible to increase the stiffness (rigidity) of the machine support structure (floor) itself to avoid resonance or amplification of vibration. In these cases, unacceptable vibration amplitudes can be significantly reduced by using vibration isolators.

Foundations Requiring Vibration Isolators

In certain applications, it is not desirable or feasible to mount a machine directly on vibration isolators.

Direct installation of vibration isolators on a machine whose frame/bed stiffness is marginal or inadequate and requires a stiff connection can cause bending, relative displacement and other problems, even when the floor is sufficiently rigid. For smaller machines, this can be remedied by securing the frame/bed to a rigid plate, thereby creating a rigid support structure, and then installing the isolators between the plate and the floor. For larger machines, the frame/bed is attached to a properly designed concrete foundation, which is then supported on the appropriate isolators for the application.

A concrete support structure (foundation, inertia block, reaction mass) is used to satisfy one or more of the following conditions:

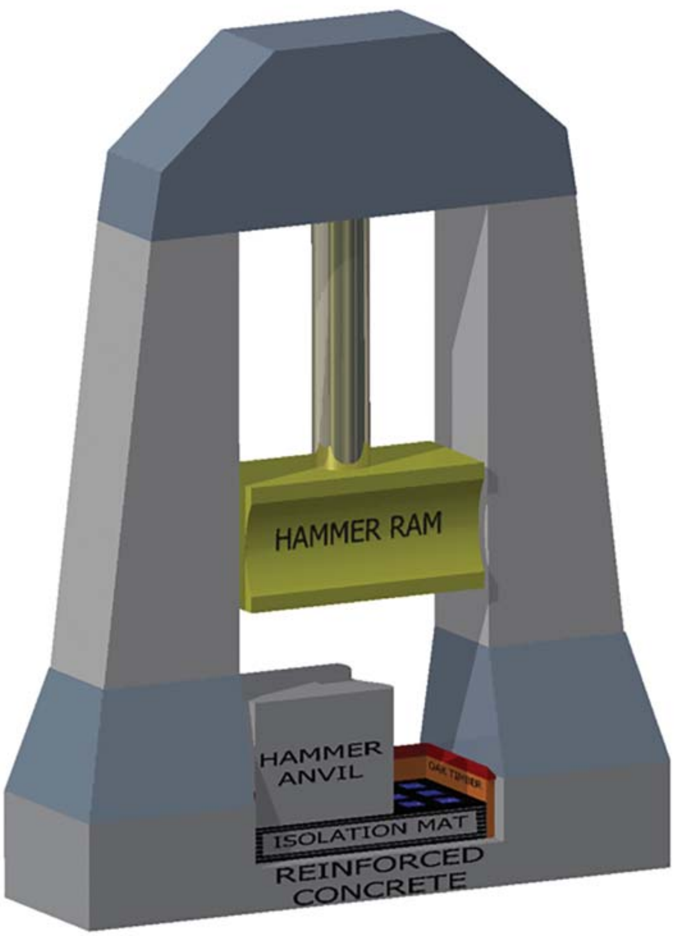
1) Provide/improve structural stiffness for the machine/equipment being isolated.

Some types of equipment do not operate properly unless supported by a rigid structure. This applies to certain types of machine tools that are not inherently rigid and therefore need a rigid support to maintain the prescribed accuracy. In other types of machinery (such as printing presses) consisting of articulated components, a rigid support may be needed to maintain the proper alignment of working parts.

Fabreeka PAL type low frequency, pneumatic isolators support and isolate a foundation having moderate displacement.

2) Increase stability on the vibration isolators by limiting dynamic deflection.

If a machine (such as a diesel engine, forging hammer or electro-dynamic shaker) generates relatively large forces during its operation, the overall movement of the machine on its isolation system tends to become excessive unless its effective mass is substantially increased. This increase in effective mass can be achieved by attaching the machine rigidly to an inertia block and mounting the inertia block (reaction mass) on isolators.



Forging hammer installed on concrete reaction mass supported by Fabreeka isolation mat.

3) Isolate the equipment/machine from the environment when installing isolators directly beneath the unit would compromise the conditions above.

In applications in which the frequency of excitation is low, the natural frequency of the isolation system must be very low to provide low transmissibility and therefore good vibration isolation. A problem often arises with a machine intended to be mounted only at its base, because a low-stiffness base-mounted system tends to be unstable and will allow excessive motion to take over.

Effective isolation may therefore be difficult to achieve. A mounting arrangement where the isolators are relocated may be used to move the isolation system's elastic center closer to the center of gravity of the machine. This will reduce the effect of "rocking," improve the vibration isolation and reduce motion on the isolators. In most applications, it is more feasible to attach the machine rigidly to a foundation (to lower the center of gravity of the machine and foundation together) and to suspend the foundation on isolators located in the same horizontal plane as the center of gravity.

A foundation or mass designed to meet the requirements outlined previously may be installed either above floor level or in a pit below floor level. Isolators used to support the foundation may be made of rubber, mat material, steel springs, air springs or other suitable, resilient material. The required size of the foundation depends on the reason for its use, the type and size of equipment and the type of isolation required.

The desired natural frequency (stiffness) and damping for the isolation system is usually established by the operating characteristics of the mounted equipment (source) and/or the isolation required (recipient). The design basis for the support foundation natural frequency assumes that the foundation is a rigid body with a stiffness much greater than the isolators. Similarly, the pit base also should be stiffer than the soil supporting it.

Design Services

Foundation Design

The function of a foundation is not only to support the weight of the machine/equipment, but also to keep the vibration levels and dynamic displacement of the isolation system within acceptable limits.

Designing foundations supporting machines that can produce static and dynamic loads requires sound engineering procedures for a reliable result. An incorrectly designed foundation is extremely difficult to correct once installed.

Engineering disciplines involved in the proper design procedures for isolated support foundations include theory of vibrations, geotechnical engineering (soil characteristics), structural analysis, and in some applications, dynamic analysis.

The design conditions and requirements can be classified into three groups: machine properties, including unbalanced forces, operating speeds; weight, center of gravity and allowable deflection; soil parameters, including load bearing capacity, and environmental requirements - *What degree of isolation is required and at what frequencies?*

Soil

The machine/equipment, foundation, isolators and pit ultimately all are supported by the soil beneath them. Geotechnical recommendations and evaluation of the soil (soils analysis) should be made and must be part of the design. This analysis includes soil characteristics, including load-bearing capacity, shear modulus, density, soil type and the composition of the soil at various depths. In the structural design of the support foundation, piles may be required depending on the load bearing capacity of the soil, high water table or generally poor soil conditions that indicate unacceptable permanent settling of the foundation will occur.

Settling, if any, should be uniform and kept to a minimum, especially when designing support foundations for equipment providing large dynamic loads/forces. If the foundation supported by isolators is used to enhance the machine frame/bed stiffness or is used as an integral part of the structural support of the machine (i.e. gantry CMM, turbine, roll grinder), then the dimensions of the foundation are defined by the machine geometry. The weight and type of machine along with a preliminary foundation size will give an indication of the soil's support requirements.

The traditional rules observed in the past of making the foundation 3 to 5 or even 10 to 12 times the weight of the equipment/machine it supports are applicable only when the foundation will be isolated by the soil and where the soil dynamic properties are known.

Structural Design and Stiffness

To be acceptable, the proposed design of a foundation or any support structure must provide a reliable structural configuration that also meets the static and dynamic criteria for the structure.

Deflections in the foundation caused by static loads or by dynamic forces/inputs should be within acceptable limits. This design approach sometimes requires modeling of the foundation, so that the real structure behavior is predetermined and errors are minimized.

The calculations for the stiffness of a foundation yield the static and dynamic behavior and stress concentration points that occur. Stresses are related to the geometry of the foundation and the distribution of loads and forces acting upon it. A stress analysis will indicate the magnitude of stress imposed by static and dynamic loading (Figure 3).

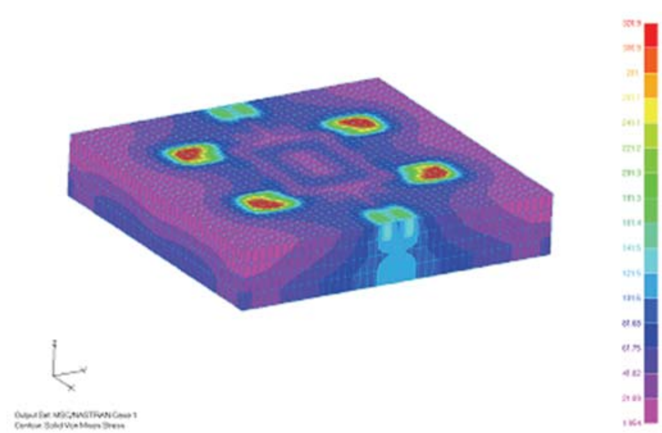


Figure 3 - Foundation stress analysis.

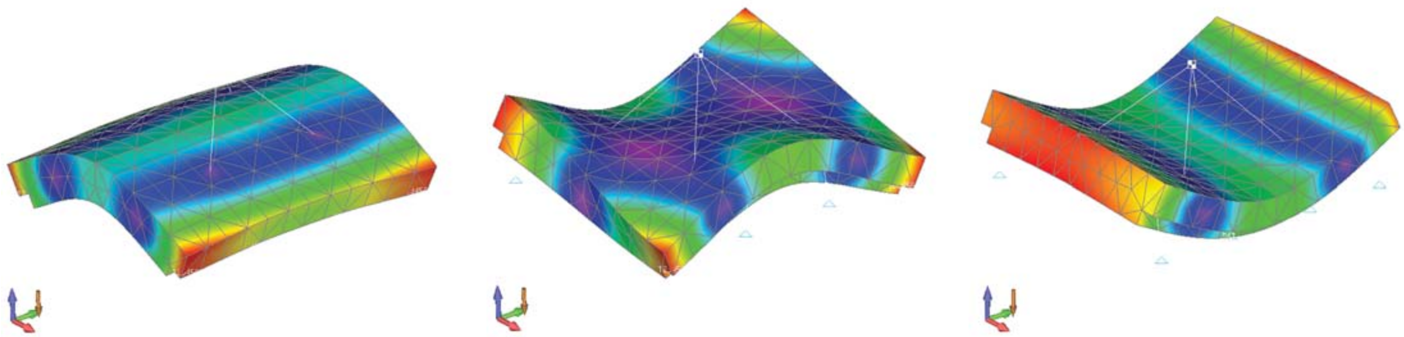


Figure 4 - Mode shapes of a support foundation.

Data on forces, such as axial, shear, torques and moments for maximum loading at each support or attachment location of the machine are necessary to predict the load conditions on the foundation. These loads are used to determine the longitudinal and/or transverse (width) reinforcement and concrete strength required, which relates directly to any deflection.

The modulus of elasticity is a key design factor in the strength of concrete. (See Figure 6.) Limits on the differential deflection allowed from one point to another on a foundation are set to avoid possible damage or misalignment of conduit and other connections. The depth of a foundation is determined by the bearing strength of the soil, the machine support requirements (structural stiffness) and in critical designs, the dynamic stiffness, which includes the foundation's natural frequency and bending modes.

Geometry and mass are important considerations in the dynamic design of foundations. However, the foundation-to-equipment mass ratios that are sometimes recommended, do little in preventing foundation vibration unless the dynamic response of the foundation is known.

A finite element analysis will define and model the mode shapes and response frequencies of the foundation, as well as the response of the isolation system and foundation to machine induced inputs and/or environmental inputs (Figure 5).

Mode shapes (stiffness of a structure in each axis) identify the physical direction of each frequency mode and any deformations, such as bending or twisting. In general, a structure's modes indicate the relative degree of structural stiffness among various points on that structure (Figure 4).

Examining mode shapes in a vibrating structure is a valuable step in adjusting vibration amplitudes at critical points by varying the stiffness, mass and damping in a structure.

Forces imposed by the supported machine can induce a high enough vibration amplitude at the natural frequency (or one of the response modes) of the foundation to cause resonance or amplification of the vibration. The single most important factor in any successful design where machine induced vibration is involved (source) is to avoid resonance between the machine and the foundation.

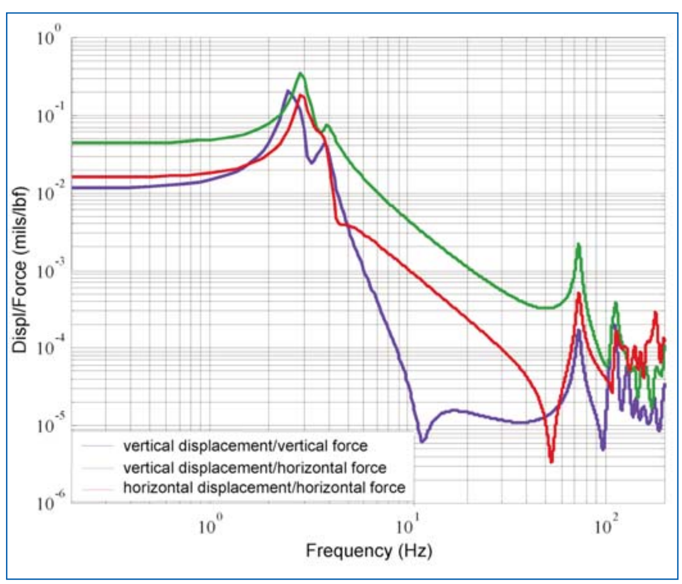


Figure 5

Amplification at the point of resonance should be addressed for environmentally induced, random or steady state vibration, although the vibration isolators supporting the foundation should provide sufficient isolation at the foundation's natural frequency to avoid amplification.

During startup or shutdown of a machine, a temporary resonance condition may be tolerated, where the support structure or even the vibration isolators are in resonance with the machine's operating frequency, especially if significant damping is available.

Data on the operating speed and forces generated by a machine, or the measured vibration amplitudes and frequencies at which they occur for a machine sensitive to vibration, are therefore required in a dynamic analysis in order to check for possible resonances.

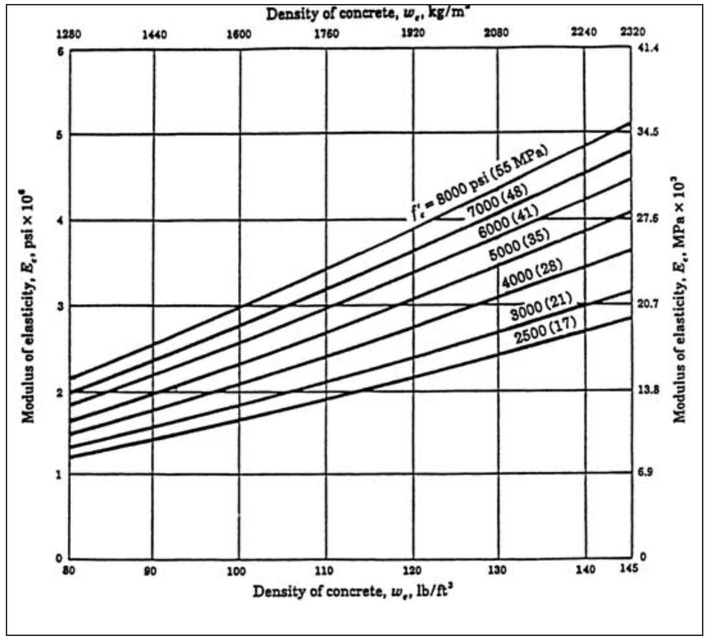


Figure 6

Concrete

An important part of a foundation's structure and stiffness is the specified concrete strength used in the design.

A specified concrete strength is easy to obtain and is often used as the only criteria. However, shrinkage control can be one of the most important factors in providing a successful project. The following are major factors controlling shrinkage:

1) Water/cement ratio (slump) of delivered concrete
2) Aggregate proportioning and size
3) Water reducing additives
4) Site conditions, such as hot, dry climate
5) Curing
6) Control joints and reinforcing

Each of these six factors needs consideration. Slump is controlled by controlling the total water per cubic yard of concrete, while strength is governed by the thickness or consistency. This thickness is determined by the ratio of the weight of water to the weight of cement.

Shrinkage is simply the reduction in volume that takes place when the concrete dries from its original wet condition down to a point where its moisture condition reaches equilibrium with the humidity in the air. Unrestrained shrinkage does not develop cracks.

Concrete sample and slump measurement of concrete mix before pouring foundation.

When designed and cured properly, large foundations result in very low concrete shrinkage while in a controlled environment. Most of the shrinkage occurs in the first two months and it is nil in the following months if the ambient environment does not change. Concrete surface sealants, if required, should be applied after most of the shrinkage has occurred.

For critical designs or for precision equipment, concrete samples should be taken at least one for each 25 cubic yards of concrete placed to check the slump. Test samples should also be taken at 7 and 28 days (assuming a 28-day cure) to verify the strength.

Design factors in the dynamic analysis of an isolated support foundation include:

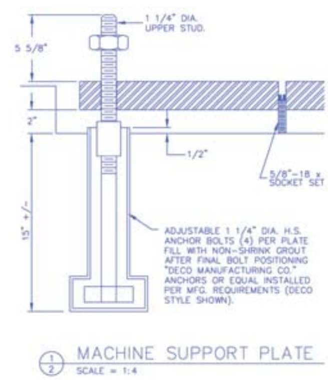
- **Unbalanced forces applied by supported equipment/machine**
- **Center of gravity of machine/equipment**
- **Natural frequency (resonance) and response modes of foundation**
- **Transmissibility**
- **Displacement on vibration isolators**

Summary

A good foundation design requires realistic analysis and supervision during construction. Stiffness in design is important both structurally and dynamically. Dynamic coupling or amplification at resonance due to the interaction of all components in the isolated foundation design can be avoided if the natural frequencies of the soil, pit, isolators and support foundation are verified.

Direct vibration measurements can be made that will render the actual frequency response of the soil and the best possible values for analysis. This is particularly important for foundations that are isolated using mat materials directly on compacted soil without using a rigid concrete pit or sidewalls.

Once the approved foundation has been constructed, the machine/equipment should be attached to the foundation to make a structurally sound connection. To achieve this, the connection should meet the rigidity and support requirements of the machine. Typical connections, which also offer leveling adjustment are anchor bolts with shims and leveling wedges. Grouting also may be required to provide a solid, load-bearing attachment.



Fabreeka RLA type pneumatic isolators provide low frequency isolation for test rigs, large reaction masses and applications where low profile, large dynamic displacement and lift height are required.

Vibration Isolators

The purpose of an isolator is to decrease the amplitudes of forced, random and steady state vibrations being transmitted into a machine or equipment support foundation. Isolators exist in many forms, including rubber, mat materials, metal coils, air bags and pneumatic isolators. The type of isolator (performance) used as the solution for an application depends on the type of machine to be isolated, static load, dynamic deflection and damping properties of the isolator.

All vibration isolators are essentially springs with an additional element of damping. In some cases, the "spring" and "damper" are separated, as in the case of a coil spring isolator used in conjunction with a viscous damper. The majority of isolator designs however, incorporate the spring and damper into one integral unit.

Important characteristics of any isolator are its load-deflection and load-natural frequency properties. The dynamic spring rate and damping of an isolator mostly are determined by the type of material used, while the stiffness (static and dynamic) is a function of the isolator design (material, shape). Static spring rate, dynamic spring rate, creep, natural frequency, damping and load deflection values vary widely from material to material and design to design. Therefore, materials or elements used for vibration isolation are chosen based on the significant differences in their performance when used to isolate specific frequencies and amplitudes.

Transmissibility

The ratio of the vibration transmitted after isolation to the disturbing vibration is described as *transmissibility* and is expressed in its basic form in Equation (1).

$$(1) \quad T = \frac{1}{1-[Fd^2/Fn^2]}$$

Theoretical, undamped transmissibility

Where Fd is the disturbing frequency and Fn is the natural frequency of the isolator. When considering the property of *damping*, the equation is rewritten as Equation (2).

$$(2) \quad T = \sqrt{\frac{1 + (2\zeta Fd/Fn)^2}{(1-[Fd^2/Fn^2])^2 + (2\zeta[Fd/Fn])^2}}$$

Where ζ represents the damping ratio of the isolator.

Natural frequency and damping are the basic properties of an isolator that determine the transmissibility of a system designed to provide vibration and/or shock isolation. Additionally, other important factors must be considered in the selection of an isolator/isolation material.
Two such factors are:

- The source and type of the dynamic disturbance causing the vibration / shock.
- The response of the isolator to the dynamic disturbance.

With an understanding of its properties, the type of isolator is chosen primarily for the load it will support and the dynamic conditions under which it will operate.

Natural Frequency, Spring Rate

Not all isolators whose isolation characteristics are based on mechanical deflection have a linear relationship between load and deflection. A common mistake is that the following equation [Equation (3)] can be used to calculate the natural frequency for all isolators if the spring rate (k) and weight (w) to support are known.

$$(3) \quad Fn = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad \text{where mass (m)} = \frac{w}{g}$$

If the stiffness or spring rate (k) is not known, the equation can be rewritten [Equation (4)], so that the static natural frequency of the isolator is a function of its static deflection (δs). This results in a determination of the isolator's static natural frequency where (g) represents the gravitational constant.

$$(4) \quad Fn = \frac{1}{2\pi}\sqrt{\frac{g}{\delta s}}$$

Theoretical, undamped static natural frequency

However, using the static, linear principle in Equation (4), the following is true:

1) Large deflections are required for low frequency isolation.
2) Damping properties are neglected.
3) Only the *static* natural frequency is obtained.
4) The isolator is assumed to have a linear spring rate.

The static deflection principle can be used only when the isolator under consideration is both linear and elastic. For example, rubber, felt, fiberglass and composite pads tend to be non-linear and exhibit a *dynamic* spring rate, which differs from the static spring rate.

The natural frequency calculated using the static deflection (δs) determined from a static load - deflection test of an isolator invariably will give a value lower than that experienced during vibration (*dynamically*).

Any isolator with a calculated natural frequency based on static deflections may not behave in the predicted way because the dynamic spring rate differs from the static spring rate.

It is the dynamic natural frequency which has to be used in calculations rather than the static.

Damping

The property of damping is neglected in the static evaluation [Equation (4)], and this can have a significant effect on the isolation efficiency. Damping in an isolator has a beneficial effect because it helps to suppress vibration, but can also lead to a loss of isolation efficiency. To appreciate the effects of damping, refer to the transmissibility curves in Figure 7.

The curves are developed using the known properties of the isolator - dynamic natural frequency and damping [Equation (2)]. Note that as damping is increased, the curve of transmissibility is flattened, so that in the region near to resonance, the curve is reduced, but in the region where isolation is required, the curve is increased. The curves show that if there is a significant amount of damping in an isolator, its natural frequency has to be reduced to retain a desired degree of isolation at the frequency ratio of concern.

The ideal isolator would have as little damping as possible in the isolation region and as much as possible at the isolator's natural frequency to reduce amplification at resonance.

With an understanding of the basic properties and dynamic characteristics of an isolator, it is possible to design for and calculate the true transmissibility of the isolator as a function of frequency. However, dynamic stiffness (natural frequency vs load) or a transmissibility vs frequency curve with the actual damping coefficient of the material is required.

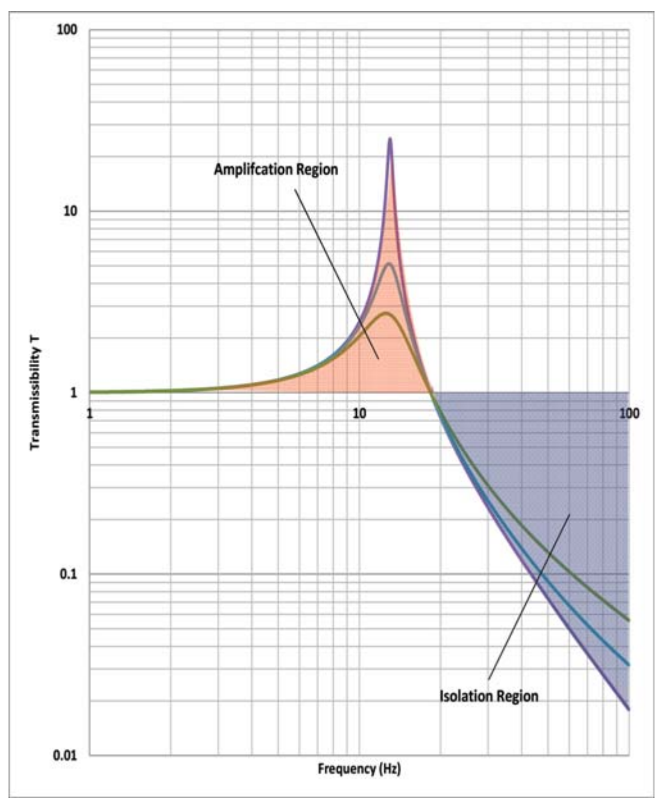


Figure 7

Figures 8 and 9 show how isolation materials can be used in constructing and isolating a foundation below floor level. A concrete pit of the required size is lined with the isolation material. Then this material is covered with plastic sheeting, and the concrete is poured on the required reinforcing rods to form a rigid foundation. The desired natural frequency is obtained by using material of the appropriate thickness and area.

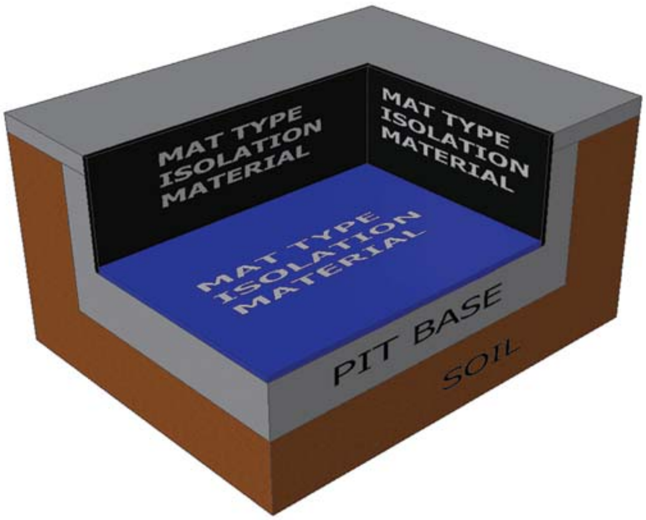


Figure 8

To obtain a low natural frequency for the isolated system, a large static deflection is required when using rubber or coil spring isolators. However, no static deflection is required when using pneumatic isolators (air springs) with low natural frequencies.

If the isolators are located substantially below the combined center of gravity of the foundation/machine, a tendency toward instability is introduced, an effect which becomes more important if the machine generates large forces during normal operation, or motion is created due to high acceleration/deceleration of moving parts. "Rocking" can be minimized by installing the isolators in positions closer to the upper surface of the foundation, supported on abutments extending inward from the walls of the pit. A more refined version of this concept is the T-shaped foundation illustrated in Figure 9. With such a design, it is possible to locate the isolators in the same horizontal plane as the combined center of gravity of the machine and foundation and reduce or even eliminate motion on the isolation system. "Snubbers" or restraints should only be used in seismic designs to prevent motion due to earthquakes and protect the supported equipment. Snubbers used for stability indicate a poorly designed isolation system.

Finally, external connections of a vibration isolated object can detrimentally affect the isolation efficiency. Mechanical attachment of conduits (service lines) including electrical, signal and other connections can affect the performance of a vibration isolation system, especially when installed under precision equipment being isolated. These connections create a good transmission path (short circuit) for vibration, which can be present at the connection source and transmitted to the support foundation. All rigid service conduits should be attached via flexible connections and in large loops to reduce stiffness and transmission.

Figure 9

Please see brochure "FAB 3000-050 Products and Services" for information on the foundation isolation products and services that Fabreeka offers. You may also contact us at any of our worldwide locations, or visit www.fabreeka.com for additional information.

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