Foundation Isolation

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Background

Machines generate vibrations, which can be disturbing in many ways; also, high vibration levels can cause machinery failure, objectionable noise levels, structural fatigue and foundation failure in the surround buildings. The reduction of machine vibration disturbances presents important challenges for engineers; hence, precision control of vibration is a must. It should start in the machine planning phase and becomes an integral part of the machine construction and plant operations. This is a critical design process that requires high level of cooperation among Civil, Electrical and mechanical engineers.

Vibrating, rotating, reciprocating and impacting equipment create different levels of machine-induced vibration and/or shock (dynamic) that is transmitted into their foundations. Rotating machine equipments such as Electric Generators (commonly used in Iraq in general and Kurdistan in particular) which are not properly balanced produce centrifugal forces that creates steady state and random vibration. Machines generating pulses or impacts, such as forging presses, hammers, centrifugal pumps and compressors are the most known sources of vibration and shock.

The reduction of vibration emission plays an important role in the operation of plant and machinery. The constant improvement in machine performance over recent years has generally been accompanied by increased speeds and cutting rates, as well as an increase in the impact power in the field of forming. Also, lack of reliability of the general electricity has led to the use of Gas-Based-Electric-Generators (GBEG) in almost every district and new building in every town in Kurdistan; consequently, an increase in the vibration transmitted to the surroundings during general power outages intermittently throughout the day. This phenomenon constitutes serious actions to better control vibration and reduce its impact on the Kurdistani people’s well being and our environment.

In order to achieve acceptable amplitudes of vibration (to be coded by the engineers union and government entities) at the source or recipient, it is 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.

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.

Isolation of machinery to prevent the transmission of vibration and noise has become one of the important phases of modern building engineering. Light weight construction and mounting mechanical equipment on the floor without proper isolation, and/or adjacent to quiet areas, increases the requirement for vibration control. The use of isolation is primarily for reducing the effect of the dynamic forces generated by moving parts in a machine into the surrounding structure

A vibration isolation problem is often schematically described by division into substructures: a source structure which is coupled to a receiver structure. The vibration isolation is yet another structure incorporated between the two structures.

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.

Vibration Isolation Principles

The purpose of isolation is to control unwanted vibration so that its adverse effects are kept within acceptable limits. A vibration isolation system prevents one object from affecting another. Such systems are used extensively to isolate machinery, civil structures (base isolation in buildings, bridges, etc.), and sensitive components from the foundation/base. Vibration isolations are used to:

1. Reduce the propagation of base vibration to the foundation, or
2. Abate the transmission of vibration energy of machinery to the base.

Every machine by its very function of operation creates a vibration or shock of varying intensity or amplitude. The requirements for isolating this vibration depend upon the local conditions of installation. Three principle factors control the selection of an isolator for a particular machine.

The first is the weight to be supported, the second is the disturbing frequency of the machine and the third is the rigidity of the structure supporting the machine.

Vibration is a force and establishing an opposed force can effectively reduce its transmission. This is accomplished by incorporating a truly resilient material, which deflects when subjected to a static load, and by so doing establishes a natural frequency of the isolation system. When the natural frequency of the isolation system is lower than the operating or disturbing frequency of the supported machine, each cycle of vibratory force finds the resilient material in the returning phase of its cycle. The effectiveness of the isolation then, is a function of the distance of return travel remaining at the time of impact.

For analyses purposes we will isolate each cycle of an individual blow. This blow drives the isolator into dynamic deflection. When the force of the blow is spent, the isolator starts its return at its own frequency. Since the frequency is slower than that of the blows, it is obvious the return will be only partial before next impact. Because the isolator possessed the energy with which to complete its return to equilibrium, the unaccomplished portion of travel represents the amount of opposed energy that will absorb the next impact. Therefore, the greater the ratio of disturbing to natural frequency the more efficient the isolation, subject to diminishing returns. It is evident any truly resilient material capable of the required static deflection, operating within its elastic limits will produce the required results. Resilience is the most essential factor of an isolator. It must have the ability to return to its original height when loads or forces are removed. Such a material, when loaded within its elastic limits, will have a long effective life.

In the case where vibrations are present due to a constant steady-state oscillation of imbalance in a machine, a precise formula may be applied with reasonable certainty of attaining desired results. In substance, this formula is based on the ration of the operating frequency of the machine or other equipment to be isolated, to the natural frequency of the isolated system. The disturbing frequency (f_{d}) of a machine can be readily determined either by measurement or by the known operating characteristics of the equipment. Generally the lowest R.P.M. in the system is used as the disturbing frequency.

The natural frequency (f_n) of a machine, set on resilient material, is a function of the static deflection of the resilient material under the imposed load. For practical purposes the natural frequency f_n is described by the formula:

$$f_n = 187.8 / d^{0.5}$$

Where d = static deflection in inches.

The ratio (f_d / f_n) establishes the efficiency of the isolation from the following formula:

$$E = 100 * [1 - 1 / \{(f_d / f_n)^2 - 1\}]$$

E = percentage of vibration isolated.
f_d = Disturbing frequency of the isolated machine.
f_n =Natural frequency of the isolated machine.

The percentage of isolation efficiency attained as a measure of the amount of reduction in the amplitude of the transmitted mechanical vibration. Refer to figure 'A' to readily select the static deflection required to attain desired isolation efficiency.

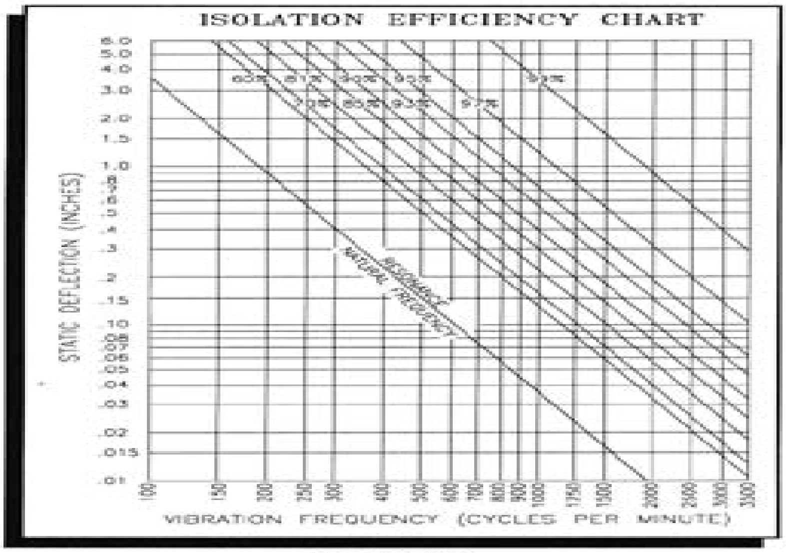


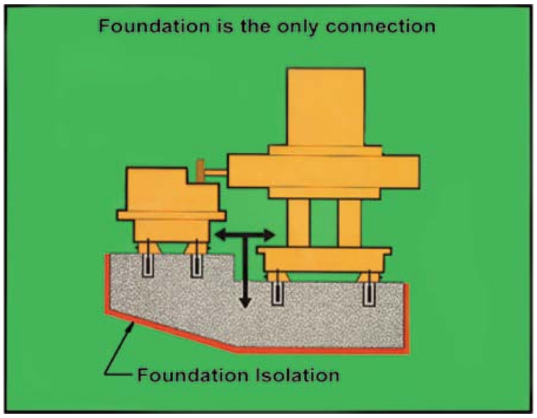
Figure 'A'

To determine the percent of isolation efficiency from figure 'A', read from the graph at the intersection of vibration (disturbing) frequency and static deflection.

Why Foundation Isolation?

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.

It is essential to locate and design the isolation in the best possible way for each specific situation. There are different options as to where along the path of vibration to deploy the isolation. In certain applications, it is not desirable or feasible to mount a machine directly on vibration isolators, and only the foundation isolation system method is sufficient.



Direct installation of vibration isolators on a machine whose frame/bed stiffness is marginal or inadequate and requires a stiff connection can cause bending, structural failure in the building, and 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 support structure, which is then supported on the appropriate isolators for the application. A concrete support structure “Inertia Block” 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.

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.

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

The machine/equipment, foundation, isolators and pit ultimately all are supported by the soil beneath them. Geotechnical recommendations and evaluation of the soil (soil 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.

Vibration isolators:

When a wave propagates in an elastic medium falls upon an abrupt change (discontinuity) in the properties of the medium, only a portion of the wave passes through that discontinuity; the remaining portion of it reflects back towards the direction from which the incident wave arrives. The magnitude of the reflected portion of the wave depends on the magnitude of the change in properties of which the wave transmits through; i.e., change in stiffness. Introducing a medium to the path of the wave in order to maximize its attenuation is called a ***vibration isolator***.

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.

Important characteristics of Isolators:

1. **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

   $$T = 1 / [(f_d / f_n)^2 - 1] \quad \textit{Theoretical, undamped transmissibility} \qquad (1)$$

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

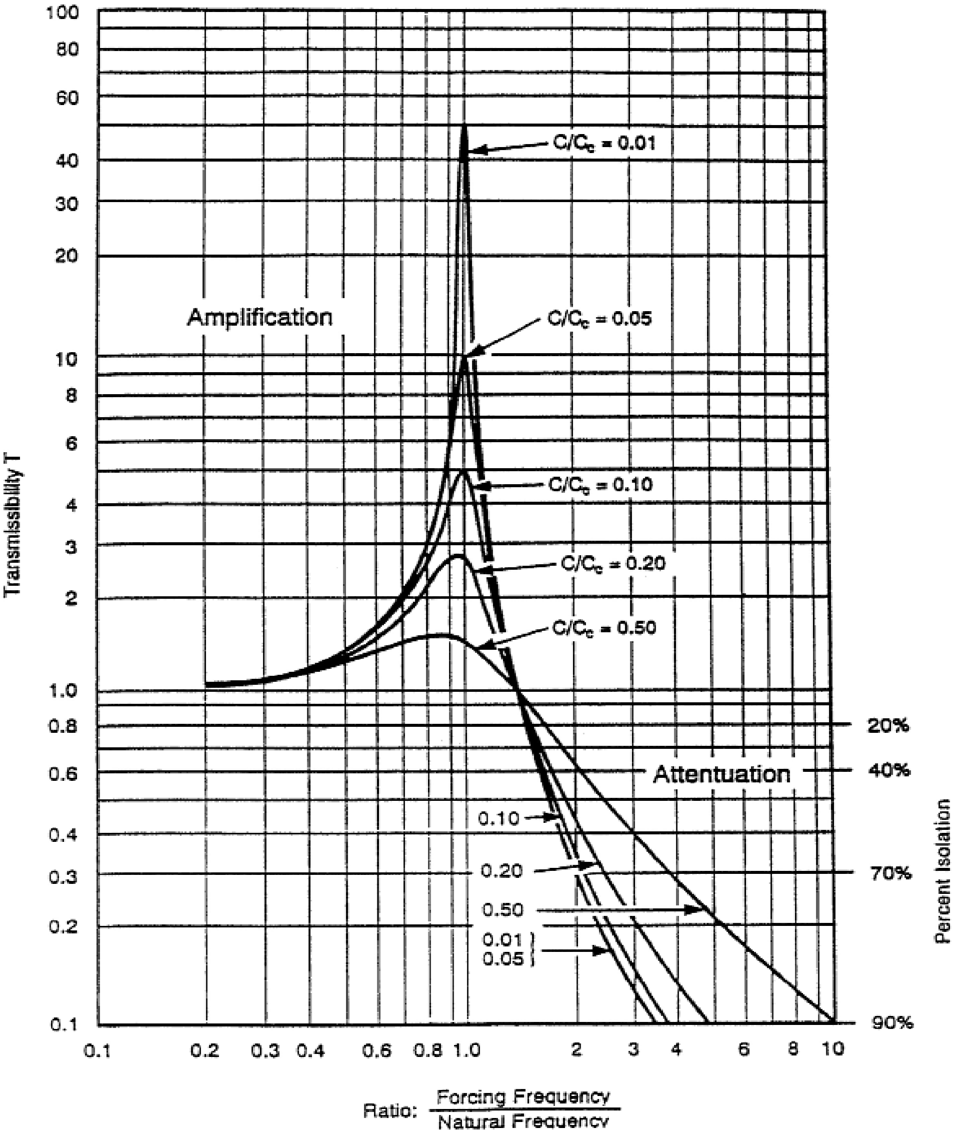
   $$T = [\{1 + (2\zeta f_d / f_n)^2\}/\{(1-(f_d{}^2/f_n{}^2))^2 = (2\zeta (f_d /f_n))^2\}]^{0.5} \qquad (2)$$

   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.



Transmissibility vs Frequency ratio for several values of damping.

Note that at the left side of the chart the curves intersect the vertical axis at a value of 1.0. This indicates that for very low forcing to natural frequency ratios the amplitude of the mechanical input to the system is equal to the output from the system. As the forcing frequency to natural frequency becomes greater, in that the output of the system is larger than the input. More simply put, the system is amplifying the input. This condition reaches its maximum when the forcing frequency ratio reaches 1:1. At this point the system is said to be in "resonance" and its output is theoretically infinite. In the real world energy is consumed by the system components and the actual amplification seen is limited.

Also, you will note that for forcing to natural frequency ratios greater than 1, the transmissibility falls rapidly back to the 1.0 value when the f_d / f_n ratio reaches 1.414, and becomes less than 1.0 for all values greater than this. It is noted that for transmissibility values falling above the "1.0" line the system will actually amplify the disturbing frequency. The region of isolation or energy reduction begins at the point that the curves cross the "1.0" line (which is 1.414 times greater than the resonance of the system).

We conclude from this chart that the further away to the right side of this point, the better isolation and less transmissibility the isolator will have.

2. 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.

$$f_n = (1/2\pi)(k/m)^{0.5} \text{ ; where mass (m) = W/g} \qquad \textbf{\textit{(3)}}$$

3. Damping

The property of damping is neglected in the static evaluation [Equation (3)], 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 Figure

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.

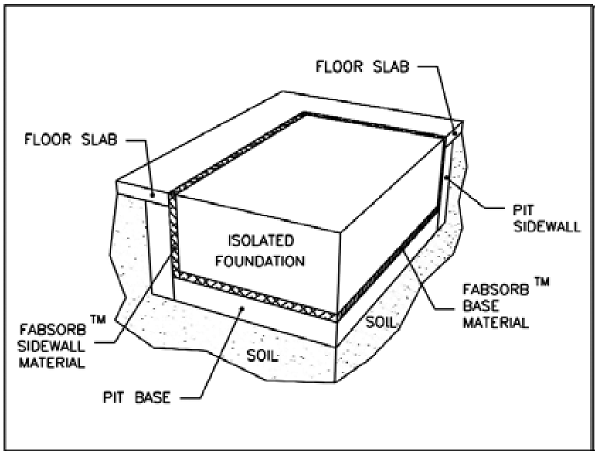
Effective isolation may be difficult to achieve. A mounting arrangement where the isolators are relocated may be used to move the isolation system's elastic center closer to the center of gravity of the machine. This will reduce the effect of "rocking," improve the vibration isolation and reduce motion 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.

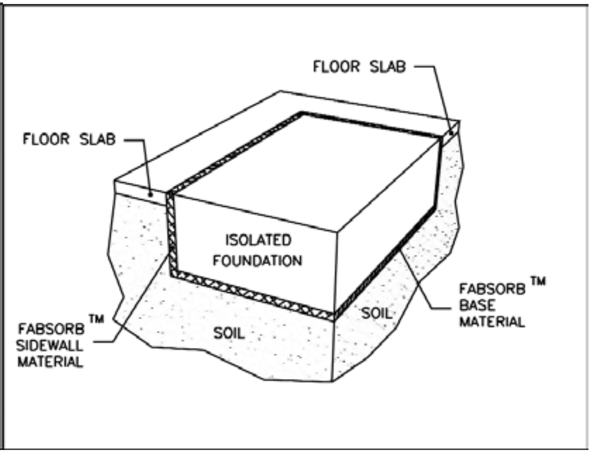
If the equipment requiring isolation is the source of unwanted vibration, the purpose of isolation is to reduce the vibration transmitted from the equipment to its supporting structure. This vibration producing equipment consists mainly of machines that apply severe dynamic forces in their supporting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

On the other hand, if the equipment requiring isolation is the recipient of unwanted vibration, 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.

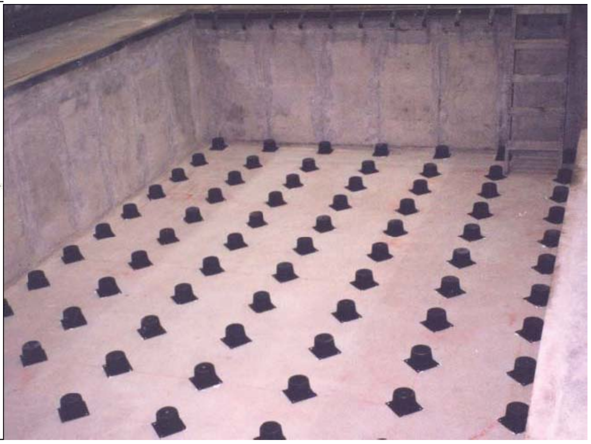
Operating frequencies of rotating/reciprocating machines often are very close to the natural frequency of their support structure (floor slab and soil). Compressors, for example, can generate vibration of substantial magnitudes at low frequencies that coincide with the natural frequency of the floor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

Types of foundation Isolators





Rubber Mat Isolators: 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.



Insulation unit isolators positioned on pit floor prior to forming the foundation above.

Air-Spring isolators are installed after the foundation has cured and the machine/equipment has been installed and anchored properly. The isolators are positioned under the foundation at predetermined support points and then activated to float or lift the foundation and machine off the pit floor.

Air bag isolators provide a low natural frequency and large dynamic stroke where dynamic deflection is acceptable.

Pneumatic isolators with lifting capacities of up to 60 tons-each are used to provide low frequency isolation for large concrete reaction masses (foundations). The isolators shown above are 72" (1,830 mm) in height and have vertical and horizontal natural frequencies of 0.7 and 0.5 Hz respectively.

Usually, coil spring isolators are used to provide shock isolation under heavy equipment and machines that produce large dynamic forces, such as forging presses, power presses and hammers. However, spring isolators also are an effective vibration isolation solution for turbines, roll grinders and automotive test equipment.

Coil spring isolator with integral viscous damping unit.

Conclusion

In some cases, the machine-induced vibration could cause structural fatigue and cracking in beams, floors, walls and other structural members. The load-bearing capability of a structural member or foundation may thus be compromised. Also, vibration could have a number of physiological effects on humans. The vibration might produce acoustic noise that is a nuisance to nearby employees. Seldom, the sound levels may be severe enough to damage hearing. Furthermore, a machine may be unable to meet precise tolerances if its own vibration levels are excessive. For all these reasons, isolating machine induced vibration is a necessity, but not a luxury. The more stable and rigid a machine has to be installed, the stiffer the isolation system needs to be, which in turn decreases the isolation efficiency. Specifically, this is the case for machines with insufficient structural, bending, and torsional stiffness. However, these machines require accurate installation and leveling. Often times only the foundation isolation system method is sufficient.

With an understanding of the basic properties and dynamic characteristics of the machine and the 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.

Good planning and communication are critical between the foundation designers, the isolation system provider, and the customer for a successful foundation design and machine installation.

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