Machine Vibrations Cause Problems Isolation Helps

Machines generate vibrations, which can be disturbing in many ways. The reduction of machine vibration disturbances present important challenges for mechanical engineers and machine operators. Therefore, precision control of vibration is a must. It should start in the machine planning phase and becomes an integral part of the machine construction.

Noise - airborne sound transmission - is now considered environmental pollution, and that is why regulations have been passed to reduce excessive noise levels in factories. They require a precise description of noise limit values for each given building area as well as descriptions of measurement and evaluation methods. Less known are the harmful effects of the structural oscillation, i.e., vibrations in solids or structureborne sound (in floors, buildings, machine frames, etc).

What is vibration?

According to it’s definition, vibration is periodic recurring movements. With this general description, naturally occurring movements can be defined as vibration, like the earth's rotation and tides as well as biological phenomena, such as biorhythms or pulses. Examples of vibration are encountered in our daily life. For instance, they are present in all string instruments or in a pendulum clock. Frequently, we do not appreciate the disturbing vibration caused by machines and equipments.

This presentation intends to show how numerous these disturbing vibration conditions can occur. The following explanation is based on the theory of simple mass oscillators and the harmonic vibrations occurring with and without damping. Note that this ideal system seldom, if ever, occurs in commonly encountered vibration isolation problems.

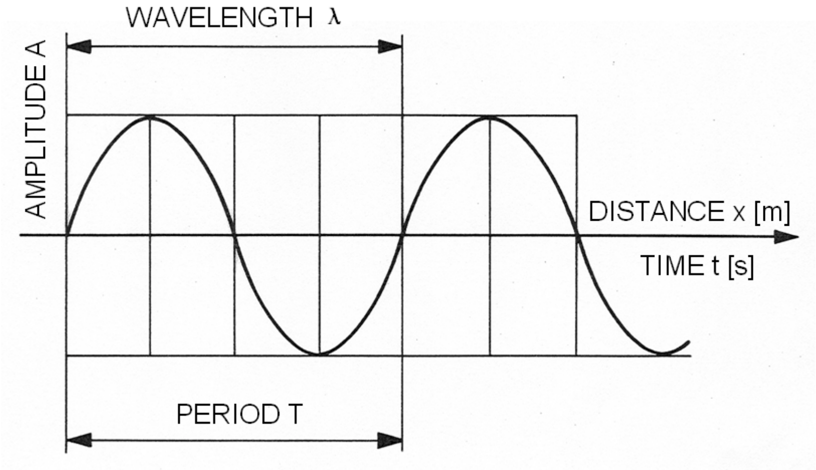


Figure 1. Harmonic vibration

Figure 1 shows harmonic vibration neglecting damping. The basic parameters of vibration are frequency, amplitude and damping, as well as natural frequency and resonance.

The **frequency f** is the number of cycles per second. Thus, it is the reciprocal of the period **T**, or time to complete one full cycle. Its units are cycles per second (s^{-1}), which is generally called Hertz (abbreviated Hz). The relation between the frequency f and the wavelength λ is given by the speed of propagation c:

$$c = f * \lambda$$

It depends on the medium in which the wave is propagated. Thus, the speed of propagation c is 330 m/s in air, 1450 m/s in water, about 4000 m/s in concrete and 5100 m/s in steel.

We should also explain the expression **structureborne oscillation**. It is vibration, which propagates in a solid body, unlike a sound wave, which propagates in the air. The vibration frequencies in the audible range are between 16 and 16000 Hz. Generally, vibrations with lower frequencies are called mechanical vibrations.

The **amplitude** is the maximum vibration level compared to the position at rest. It defines the "strength" of the oscillations. Amplitude and frequency are not linked, because the amplitude can be either large or small for each given frequency. For instance, the frequency of a pendulum is only determined by its length. Its frequency remains the same regardless of its oscillation amplitude.

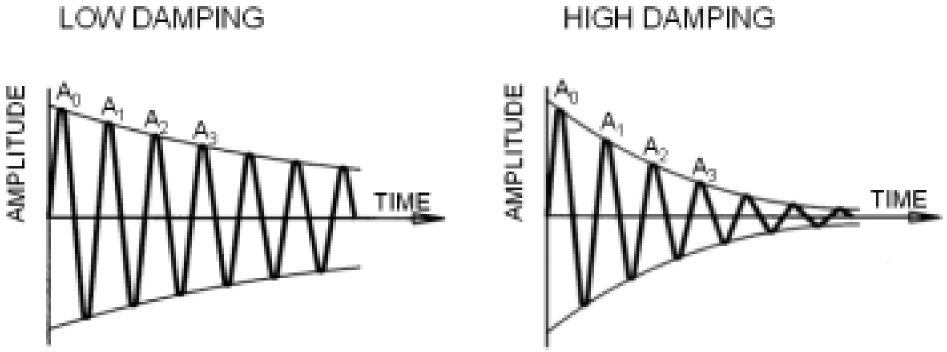


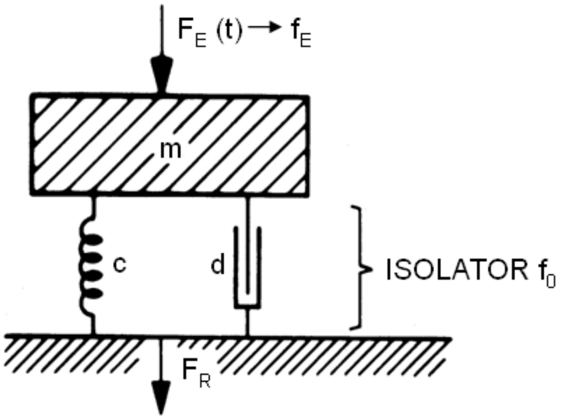
Figure 2: Damping

The **damping D**, shown in Figure 2, demonstrates the vibration amplitude decrease of a freely oscillating spring-mass-system through friction over time. The logarithmic nature of this curve is called logarithmic decrement by physicists. From the damping (D), one can directly derive the dissipation factor (d), the decay constant (δ), the decay time (T) and the resonance rise, quality factor (Q). The damping is based on the conversion of energy into heat. On the one hand, the damping leads to reducing amplitude; on the other hand, it prevents a very large amplitude increase at the point of resonance.

The **natural frequency f_o** is the frequency of free vibration of a system, which oscillates at its equilibrium position without any excitation. (We should add here that all bodies have six degrees of motion - three translational and three rotational - and have also six natural frequencies, theoretically.) Every mass, structure, floor, building, and in fact every physical object has a natural frequency, which can only be calculated for the simplest conditions. Usually, it can be measured by impact or impulse quite easily. For a dynamic process, the natural frequency f_o is significant, when it is near the forcing frequency $f_{E,}$ or coincides with it. This is commonly called the **resonance point**. In this case, the amplitude could rise theoretically to infinite values, if there were no damping, which could lead to the destruction of the system.

Vibration isolation

Generally, vibration isolation is imposed to separate a dynamical system from its environment by means of an isolator which has a considerably different natural frequency, compared to the forcing frequency of the applied force.



m = mass
c = spring constant
d = damping coefficient

f_0

f_0 = natural frequency of isolator
f_E = forcing frequency

$\eta = \frac{f_E}{f_0}$ frequency factor

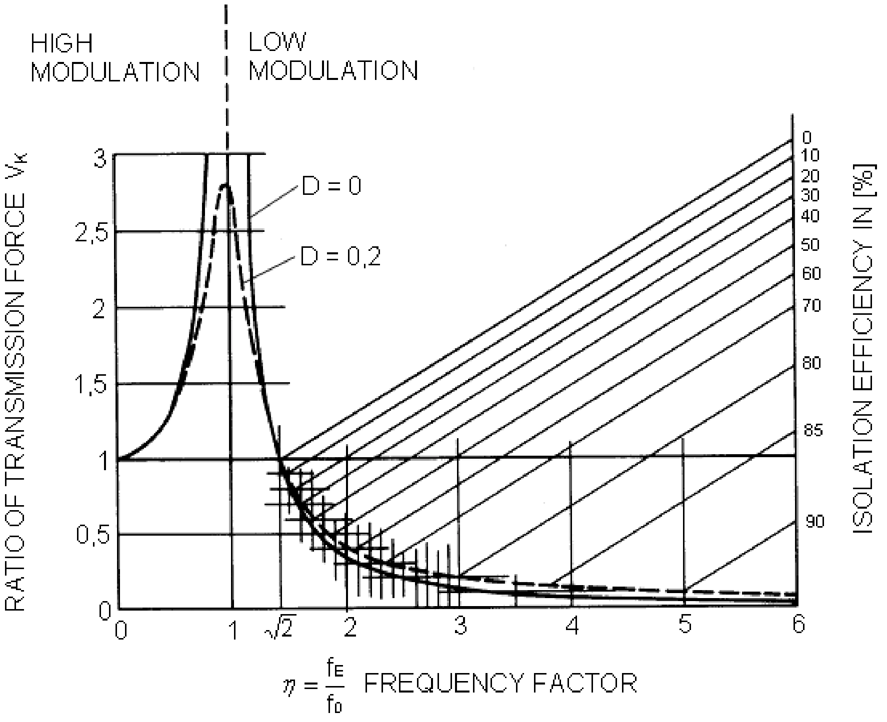
F_E = applied force
F_R = transmitted force

$V_K = \frac{F_R}{F_E}$ ratio of transmission force

Figure 3: Vibration isolation of a dynamic system

Figure 3 shows such an isolated system. It is of interest to note the ratio of the transmitted force to the applied force. This ratio is called the ratio of transmission force (V_{K}), which is also a function of the frequncy factor η (s. Figure 4)

$$\eta = \frac{f_E}{f_0}$$



$$V_K = \frac{F_R}{F_E} = \sqrt{\frac{1+(2D\eta)^2}{(1-\eta^2)^2+(2D\eta)^2}}$$

ISOLATION EFFICIENCY $J = 1 - V_K$

Figure 4: Ratio of transmission force V_K as a function of frequncy factor η

One can also see the damping effect in Figure 4. The ratio of the transmission force (V_K) is restrained at a limited value with damping (D = 0.2) at the resonant point ($\eta = 1$). And with no damping (D = 0), this ratio (V_K) would increase infinitely, which could lead to destruction with an extremely large vibration amplitude.

If there is no damping, D = 0, the above given equation for the ratio of transmission force (V_K) can be simplified to

$$V_K = \frac{1}{|1-\eta^2|}$$

And for $V_K = 1$, the frequncy factor

$$\eta = \sqrt{2}$$

can be found easily. Above this value, the isolation will be effective. The higher the frequency factor, the better the isolation efficiency

$$J = 1 - V_K$$

Obviously, it will cost much more for a system with

$$\eta > 3$$

Usually, it is not economically feasible.

Of course, this theoretical method of calculating vibration isolation is accurate. In practice, it can be confirmed with steel springs, because they exhibit a linear spring rate, and almost no damping. However, with the use of other elastic materials, in particular a mixture of several different materials, one notices that below the resonance range of about $\eta = 0.5$, the vibration acceleration is reduced, and there is still an isolation effect.

In addition to the non-linear spring rate associated with elastomeric isolation materials, it should also be pointed out that one cannot derive the natural frequency from the static deflection, unlike steel springs. For these materials, the natural frequency is a function of the specific load, and should be measured in the laboratory. Therefore, the measured deflection of an isolation pad under loading is not be called resilience, but rather static deflection.

Vibration measurement and analysis

In practice, such ideal systems, as described above, can rarely be found and the calculation of component natural frequencies is generally expensive. Also the frequencies of the primary disturbances are not usually known and are difficult to calculate. The frequencies associated with a certain speed often appear as small amplitudes. Generally at machine feet, under which levelling devices are mounted with vibration isolation pads, there are predominant ranges of frequencies, which are driven by the vibration of the machine frame rather than by the operating speed.

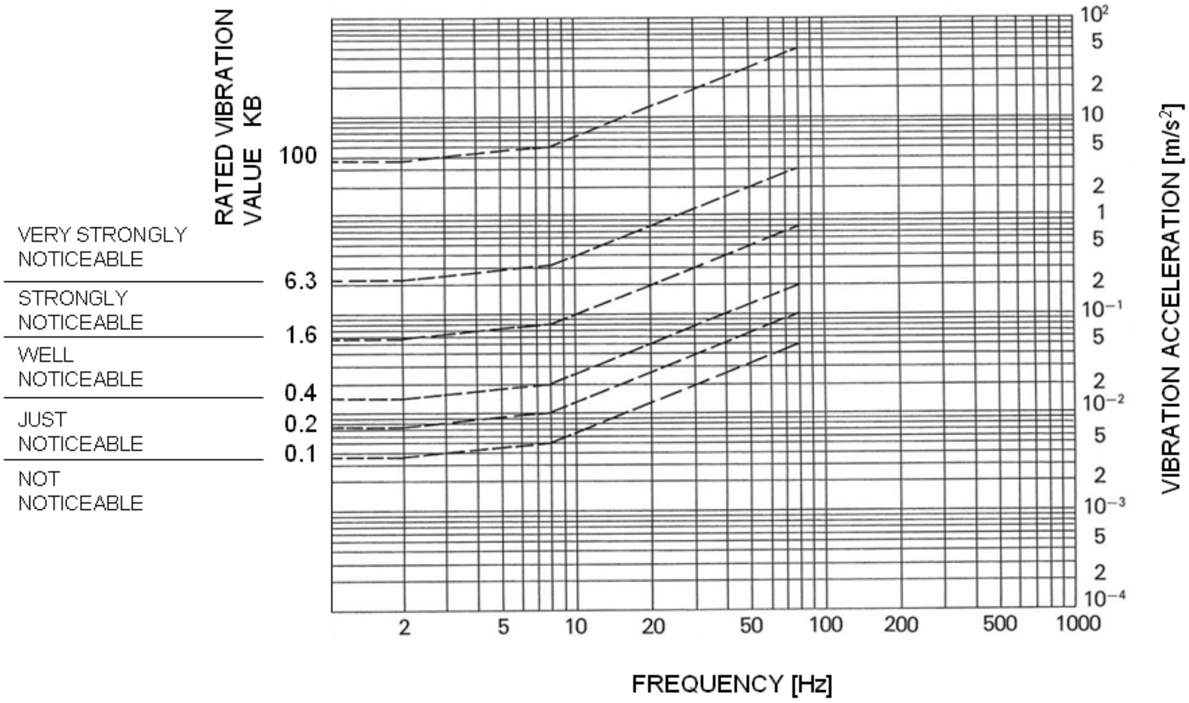


Figure 5: Measured values and rating of mechanical vibrations

Consequently, the measurement of vibration is very important. The natural frequencies of the ground or the floor as well as the disturbing frequencies of the machine or the surroundings are often analyzed. For fast and precise measurements a vibration frequency survey is often conducted. The amplitude of oscillation acceleration (m/s^2 or g) is normally measured. It can be recorded as a function of the time or frequency domain.

With modern instruments, it is also possible to measure the oscillation velocity (m/s) and the oscillation displacement (mm) directly. As in acoustics, the subjective perception of vibrations is obviously frequency-dependent for the structural oscillation. Thus, the results of such measurements are less suitable for judging the disturbance of a vibration. Therefore, a weighted vibration value KB was defined (VDI 2057, DIN 4150). Figure 5 represents a table of these KB-values with their subjective strengths. This table shows that low frequencies are more noticeable than the higher ones. Similar to the noise limit values, DIN 4150 standard also gives limit values for day and night in different areas, such as industrial, residential and mixed zones.

Vibration-isolated machine installation

The requirements for machine installation are usually conflicting: The machine must remain steady with no motion, while it should to be vibration-isolated at the same time. It must also be capable of being easily installed, and moved quickly but, should not slide. Levelling and relevelling should also be very accurate, but the levelling devices have to be firm and stable.

Faced with these demanding requirements as well as availability of numerous types of levelling devices, and vibration isolation materials, the project manager or person responsible for maintenance may be confused with the choices. Therefore, it is highly advisable and even essential to contact a levelling and isolation specialist to take advantage of improved working conditions, enhanced machine performance, etc.

Firms that provide not only leveling devices but also complete solutions (consulting services, engineering, measurement, materials, installation and other services) should ideally be contacted at an early stage in the program. Especially, for projects such as new buildings and the conversion of manufacturing plants where sensitive machines will operate or where machines with disturbing impact loads will be working, it is of the utmost importance that attention be paid to the design of the machine foundations with regard to vibration isolation. Therefore, only a specialized company with extensive engineering application experience can offer an effective service to recommend solutions that best suit the customers particular problems.

Practical considerations

As far as vibration-isolated machine installations are concerned, one should note the difference between active (internally generated disturbances) and passive (externally generated disturbances) isolation. With **active vibration isolation**, the surroundings are protected from disturbing vibrations which are generated by nearby machines.

Examples: presses, punching and cutting machines, mixers,
diesel generators, compressors, and heat pumps.

Passive vibration isolation is intended to protect particularly sensitive equipment from disturbing environmental influences. For instance, these external disturbances might include the influences of railway lines, road traffic, cranes, forklifts, or any other similar inputs.

Examples: grinders, measuring instruments, scales, electronic microscopes.

The question, as to whether an application requires unit isolators, a foundation isolation system, or both, has to be examined carefully. For economic reasons, a unit isolator is preferred. But, unit isolation may be unsatisfactory for support critical machines which have to work perfectly and remain absolutely stable and rigid. 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 levelling . Sometimes only the foundation isolation system method is sufficient.

Figure 6: AirLoc Jacmounts

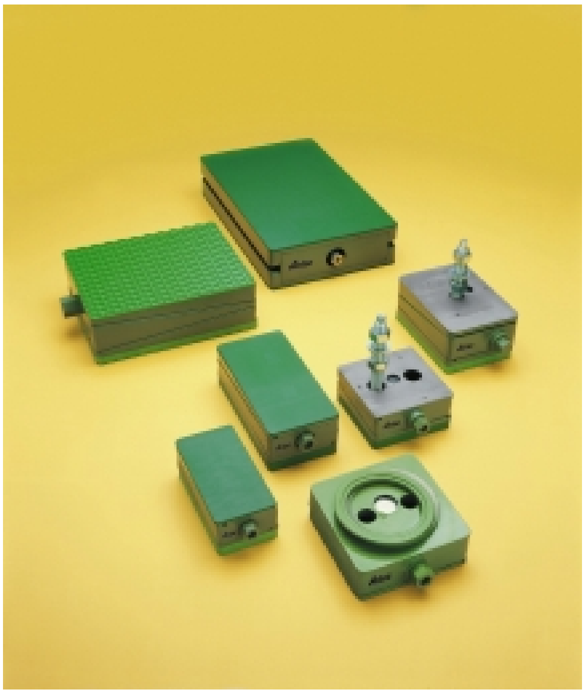


Figure 7: AirLoc Precision Wedgmounts

For **unit isolation**, the AirLoc product line provides a very wide range of levelling devices, such as Jacmounts and precision Wedgmounts (Figure 6 and 7). When machines have to be anchored to a foundation, there are basically two possibilities, namely a rigid clamp levelling-anchoring system (with no isolation at all) and a bolt through system with isolation to reduce the structural vibrations. These systems are specially designed to give a high degree of levelling precision (to 1/100 mm) and stability.

Experience shows that many machines, which formerly were anchored, or grouted, can now be installed on freestanding Wedgmounts without any problems. It is possible to achieve an optimal compromise between vibration isolation and stability, if a suitable isolation material is installed under the levelling devices. Thanks to the high coefficient of friction of AirLoc isolation materials (about 0.8), very high horizontal forces can be tolerated. In extreme cases with severe lateral loads, isolated horizontal supports ensure absolute stability. This allows for installations, such as plastic blow-molding machines with horizontal forces, to be installed without a problem.

Figure 8: Foundation pit constructed with AirLoc isolation system for the reduction of vibration and structural disturbances

Generally, a **foundation isolation** system is designed with isolation which is not placed directly under the machine, but rather under the machine inertia base foundation. Such a machine foundation consists of an inertia block consisting of concrete poured into a foundation pit (Figure 8). When dealing with smaller equipment, the machine foundation can be a concrete slab raised off the floor. However, larger isolated machine foundations are generally constructed within foundation pits below the normal floor level.

During the design of foundation isolation systems, there are three design considerations which have to be taken into account:

- The first consideration is to increase the machine stability as well as to attain torsional stiffness. Many machines do not function properly without precise alignment. In this case, the foundation block can be considered as an integral part of the machine.
- The second consideration is to improve the isolation effect. The concrete foundation block gives additional stability, as the foundation block area is larger than the machine dimensions. The isolation system under a foundation block is substantially softer, with lower resultant frequencies than a rigid support.
- Finally, the inertial mass of a foundation block helps to improve the damping effect of the entire isolation system.

The **double isolation system** is a combination of both above mentioned methods, unit isolators and foundation system, for isolating machines:

> a relatively stiff, but vibration-absorbing unit mount directly under the machine, which is installed on an isolated foundation with lower frequencies.

With the double isolation, a remarkably low frequency isolation system can be obtained. However, the machine installation will be very stable. Already, several hundred rotary presses have been set up using this method successfully. These are machines which weigh from a few hundred to several thousand tons, and are usually between 15 to 80 m long. The project manager for this type of new construction said: "It is natural that a machine inertia base foundation, once it has been installed, and even though it is not visible, should be considered - unpretentiously - as the most important part of the construction."

Machine installations in seismic regions

Globally, about 80 % of all earthquakes occur in the circumference of the Pacific, the so called ring of fire of the Pacific. This includes Japan, the Philippines, the southwest Pacific as well as the west coasts of South, Central and North America. In Europe, seismic activity occurs predominantly in the Mediterranean region. Mainly, these are the North African costal zone, Italy, the counties of the former Yugoslavia, Greece, Turkey as well as the southern mountain area of the Alps. The Alpine regions of Switzerland and Austria belong to the affected zone. Even in the north of the Alps, slight earthquakes are usually observed. It is connected with the tectonics of the Rhine Rift.

In these regions, the question of vibration-isolated machine installations combined with an earthquake safety restraint system is very necessary. Because the protection from vibration, due to less than destructive earthquakes, will prevent equipment damage and production stoppages. Normally, the horizontal components of the seismic motions cause the destruction of buildings and machines. Depending on ground conditions, the disturbing frequencies due to earthquakes range from 0.5 to 2.0 Hz. These are very low frequencies. It is obvious that the machine mount should be as rigid, stable and strong as possible to resist earthquake forces. Furthermore, adequate vibration isolation, such as the above mentioned double isolation systems, should also be provided. For protection against seismic forces, the machines are normally restrained on the foundation by horizontal supports. In this case, an isolation material has to be selected between the support and the machine. The dimensions of the supports are determined on the basis of the horizontal acceleration forces calculated for the specific earthquake zone. The supports have to be anchored to the foundation accordingly.

Where seismic accelerations introduce the risk of machine overturning forces, the machine feet with their Wedgmounts must be fastened to the foundation with properly rated bolts and anchoring system. Additional risk exists when the machine is relatively tall with a small footprint. A typical case would be large rotary printing presses.

Experience over the past 50 years indicated that the above provisions were not always necessary for earthquakes which occurred in Western Europe at magnitudes of up to 4.0 on the Richter scale. One special experience was an earthquake with a magnitude of 4.0 in the Lower Rhine region, where rotary printing presses were installed using the "double isolation" method without any horizontal supports. It was the non-skid effect of the isolation pads underneath the Wedgmounts that prevented horizontal shifting of the double-isolated machines during the earthquake, while similar machines without any such vibration isolation sustained damage.

Materials for vibration isolations

The most important element in vibration isolation is the isolation material itself, which in turn depends on its characteristics and performance. There are a lot of materials used for isolation which can be classified into the following cartegories:

- springs
- elastomers (natural and synthetic)
- pvc cork and fiber filled pads
- composite materials
- natural and synthetic foams

All these materials have advantages in different types of applications. Steel or air springs, for instance, are effective for very low frequencies (1 to 5 Hz). Cork is a good damping material. Elastomers finds wide application because of their vulcanization into various shapes and sizes. Synthetic elastomers, such as neoprene and nitrile compounds, have very stable environmental properties, with natural frequencies down to 7 Hz. Poly vinyl chloride (pvc) pads of composite materials, due to their construction and method of manufacture, have very stable properties, with natural frequencies down to 25 Hz. With combinations of various materials, natural frequencies of isolation pads can reach lower than 15 Hz. With specially constructed designs, pads with natural frequencies of 6 to 7 Hz can be manufactured. By utilizing these isolation materials, nearly all vibration problems can be solved.

It should be noted that the practical characteristics for all these isolation materials can be measured and confirmed by laboratory tests. Particularly, in the case of non-homogeneous pvc materials, there is no accurate mathematical relationship for their physical characteristics. Other properties, such as durability, damping and creep, must also be defined and quantified in the lab for each characteristic. Due to these circumstances, it is advisable to trust experienced specialists, who have continued to improve their isolation products along with proven application knowledge and state of the art test equipment.

From this point of view, AirLoc Schrepfer Ltd. is a highly specialized enterprise which has been known worldwide in the field of engineered levelling and vibration control products for more than 50 years. This long established background and profound know-how regarding vibration isolated installation methods, is evident specifically by successfully levelling and isolating many large rotary printing presses. Other applications, such as vibration isolation and levelling for all kinds of industrial machines, can also be solved professionally by the experts at AirLoc Schrepfer Ltd.