Vibrations and its Isolation
Basics & Solutions

Content list:
1. Introduction ......................................................................................................................................1
2. Vibration sources........................................................................................................................1
3. Vibration isolation techniques..................................................................................................3
4. Transmissibility (comparison active – passive antivibration solutions).................................5
5. Advantages of active isolation .................................................................................................5
6. Low Power technology LP (new & unique) ............................................................................6
7. Comparison passive to active isolation (example) .................................................................6
8. Table top systems of the TS-series .........................................................................................7
9. Modular concept of the AVI-series .........................................................................................8
10. Vibrations analysis (on-site) .................................................................................................9
11. Analysis example ....................................................................................................................11

1. Introduction

Modern technologies in the field of high-sensitive measurements, high-resolution microscopy, and the raised quality standards for high precision manufacturing requests an increasing demand of effective vibration isolation systems to stop the influence of disturbing ambient vibrations (e.g. building, floor, traffic, machinery, sound, airflow).

Blurred microscope images and strips within scanning modes of high resolution microscopes (e.g. SEM, AFM, TEM, etc.) are further negative effects cause by external disturbances. Possible vibration sources, different vibration isolation techniques, and the possibility of a vibration analysis on-site will be described shortly in the following chapters.

2. Vibration sources:
Beside disturbances caused by the measurement system itself (e.g. by integrated motors, pumps, or coolers) external vibrations in a laboratory or production facility can be transmitted via the floor, connected cables or tubing. The origin of this vibration sources are:

**Building vibrations (caused by sources from outdoor):**
- Environmental machinery and traffic (cars, tramway, or subway) can induce vibrations at the lower and middle frequency range (5-100 Hz).
- Wind flow can induce low frequency building vibrations that come with higher amplitudes in the horizontal direction. It increases at higher floor and can reach great amplitudes (up to 500 µm/s) at lower frequencies.
- Seismic movement extends in vertical and horizontal direction along the entire building and induces vibrations at very small frequencies (0.5 – 10 Hz). The amplitudes can vary widely.

**Room vibrations (caused by sources from inside)**
Local vibrations inside a laboratory or a manufacture plant come from:
- Elevator and air conditioner
- Pedestrian inside the house & laboratory and opening/closing doors
- Motors, pumps, and coolers in the closed surrounding.

The frequencies vary from the lower up to the middle range. Floor vibrations, e.g. caused by walking people and/or opening/closing doors appear at frequencies that are mostly very closed the natural resonance of the building, typically around 10 Hz (2-15 Hz).

Motors, pumps, and cooler can cause vibrations typically in the middle frequency range (e.g. 50 Hz and multiple). The amplitudes closed to the vibration source can be relative high (up to 200 µm/s) but decreases rapidly by distance.

In addition to this the location inside of the building has also a big influence regarding the dimension of the disturbances. Generally, the effect in the upper floors is greater in relation to the ground floor.

Workstations and support frames come with natural resonances and can oscillate. A good table comes with the lowest resonance frequency well above 100 Hz.

---

**Natural resonances:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors</td>
<td>8 … 25 Hz</td>
</tr>
<tr>
<td>Railways</td>
<td>40 … 80 Hz</td>
</tr>
<tr>
<td>Vehicles</td>
<td>1 … 2 Hz</td>
</tr>
<tr>
<td>Air spring</td>
<td>0,5 … 3 Hz</td>
</tr>
<tr>
<td>Springs</td>
<td>4 … 10 Hz</td>
</tr>
<tr>
<td>Rubber</td>
<td>5 … 20 Hz</td>
</tr>
<tr>
<td>Suberic</td>
<td>5 … 20 Hz</td>
</tr>
<tr>
<td>Industrial building</td>
<td>max. 12 mm/s</td>
</tr>
<tr>
<td></td>
<td>10 … 30 Hz</td>
</tr>
<tr>
<td></td>
<td>5 - 8 mm/s</td>
</tr>
<tr>
<td></td>
<td>30 … 60 Hz</td>
</tr>
<tr>
<td>Running/Jumping</td>
<td>1,5 … 3,0 Hz</td>
</tr>
</tbody>
</table>

---

[1]
The vibration analysis will be introduced in chapter 10. The power spectrum is the most commonly used algorithm (see page 9 for details).

The following figure displays the generic vibration criteria for the upper limits by Colin Gordon.

![Vibration Criterion (VC) according to Colin Gordon](image)

![Figure: Vibration Criterion (VC) according to Colin Gordon [2]](image)

### 3. Vibration isolation techniques:

There are different isolation techniques. Principally, it can be classified between passive, semi-active, and active damping systems.

**Passive systems:**

Passive damping systems are only based on the isolation by its mechanical properties and without an additionally external energy supply to compensate the occurring vibrations. Typically pure passive dampers consist of air- respectively metal springs or rubber pads. Passive solutions isolate well at middle and higher frequency ranges (e.g. greater than 30 Hz).

Passive systems are built up as soft systems to reach a maximum of isolation. Soft systems come with low natural resonances but relative long recovery time from shock (several seconds).

In contrast to these systems active anti-vibration systems like the AVI- and TS-series are designed as a stiff system with a response time of less than 10 ms.

### Optical Microscopy:

- OP-room (resolution until 100x)
- VC-A (resolution until 400x)
- VC-B (resolution until 1000x)

### VC-A:

- Microbalances, projection aligners

### VC-B:

- Lithography incl. steppers

### VC-C:

- Lithography down to 1 µm

### VC-D:

- Standard REM & TEM
- Electron beam systems
- Atomic Force Microscopy (AFM)

### VC-E:

- Nanofabrication
- Scanning Electron Microscopy

$v_{\text{rms}} > 200 \, \mu\text{m/s}$ are sensible
Because of system relevant natural resonances (typically 0.8 – 12 Hz) pure passive systems even amplify disturbances at those low frequencies. As building resonances (typically 2-15 Hz) are often too close to the natural resonances of the passive systems. Vibrations caused by pedestrians, doors, and traffic often can not be isolated sufficiently. Most air based isolators damp only in the vertical direction and floats on air cushion horizontally. Some Scanning Electron Microscopes uses a pendulum to compensate vibrations in the horizontal direction. Anti vibration systems on the basis of metal springs are available for the isolation in one or three directions.

**Semi-active systems:**

Semi-active systems use inner factors and parameters to compensate existing disturbances with external power and are not controlled by the belonging state variables (forces and kinetic momentum).

Typical examples are passive isolators with adjustable characteristic or position controlled air-springs, also known as active-pneumatic systems.

Semi-active systems are normally not free of calibration. The controller gain has to be adapted individually to the resonance frequency.

**Active systems (also called dynamic controlled systems):**

The supply of external power for vibration cancellation will be dynamically correlated in that way that the relevant state variables (force and kinetic momentum) will be influenced directly.

There are two different types of control systems:

**Feedforward** uses an open control loop. The floor vibration will be detected and a counter force, controlled by an electronic unit, will be generated to compensate the movement. The next behaviour of the system will be estimated via the transmissibility function and the present correction signals adequate modified. The controller gain has to be adapted to the resonance frequency.

**Feedback-control** consists of a closed system and is calibration-free.

Two structural principles of active vibration isolation have to be differentiated:

- Isolation through compensation of displacement: mechanical impedance will be decreased
  ⇒ The isolation system becomes softer (ideal infinite soft).

- Isolation through force compensation: mechanical impedance will be increased.
  ⇒ The isolation system becomes stiffer (ideal infinite stiff)

The AVI- & TS-series are based on force compensation and comes with an inherent stiffness that lead to the short response time of less than 10 ms.
4. Transmissibility:

Comparison of passive and active vibration isolation:

5. Advantages of Active Vibration Isolation

The active vibration isolations offered by HWL (AVI- & TS-series) comes with an inherent stiffness (500x greater than that of a 1 Hz resonance passive isolator), a response time of less than 10 ms, and - due to dynamic feedback control - a lack of any low frequency resonance.

Advantages of active versus passive systems:
- small size
- lack of any low frequency resonance
- inherently stiff (500x greater than that of a 1 Hz passive isolator)
- rapid recovery time from shock (10 ms)
- no air required
- no set up time
- includes all six translational and rotational vibration modes
- superior to any passive system

6. Low Power technology LP (new & unique)

The above mentioned active vibration isolation systems have been introduced to the market in the late 1980s. For more than 20 years electrodynamic force transducers (voice coils) has been used as actuators. Since the beginning of 2008 (AVI) and 2010 (TS) these active systems will be equipped with a complete new und unique technology. The electrodynamic force transducer has been replaced by a unique low power piezoelectric motor. The total power consumption has been strongly reduced (down to approx. 1/5 of the previous version). Heating up of the systems within a housing (dustcover or acoustic box) is now impossible.

This new technology comes without any magnetic stray fields and no electromagnetic pollution to upset delicate instruments. Moreover, the Isolation has been further improved!

Unique feature: Low Power technology (LP)
- no electromagnetic pollution to upset delicate instruments
- complete absence of any magnetic stray fields
- no heating up by strongly reduced power consumption
7. Comparison of passive versus active isolation

Example: mirror surface detected by a profiler

**not isolated:**

![Broadband vibration spectrum](image1)

**passive isolated (metal spring system):**

![Broadband vibration spectrum](image2)

Frequencies (>30 Hz) will be sufficient isolated by the passive system, low frequency vibration (close to natural resonances) unfortunately not.

**active isolated (dynamic control on):**

![Broadband vibration spectrum](image3)

The dynamic control takes care that the whole frequency range will be isolated effectiv and quick (10 ms response time).

See page 11 for further example!
8. TS-series (active table top platforms)

Table top applications can be very easy isolated by the TS-series. The TS-platforms are available in 3 different dimensions, optional with stainless steel top plate and a grid with tapped holes.

<table>
<thead>
<tr>
<th></th>
<th>dimensions</th>
<th>load</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS150/LP</td>
<td>400 x 450 x 78 mm³</td>
<td>0 - 150 kg</td>
</tr>
<tr>
<td>TS140/LP</td>
<td>500 x 600 x 84 mm³</td>
<td>0 - 140 kg</td>
</tr>
<tr>
<td>TS300LT/LP</td>
<td>600 x 800 x 120 mm³</td>
<td>0 - 120 kg</td>
</tr>
<tr>
<td>TS300/LP</td>
<td>600 x 800 x 120 mm³</td>
<td>0 - 300 kg</td>
</tr>
</tbody>
</table>

**Standard**
- aluminium top plate

**Optional**
- stainless steel top plate
- grid M6 x 25 mm
- grid ¼”- 20 x 1 inch

**Key applications:**
- Scanning Probe Microscopy (AFM, STM)
- Near Field Optical Microscopy
- Optical Microscopy
- Interferometry
- Profilometry
- Micro- & Nanoindentation
- Nanolithography
9. AVI-series (active modular solutions)

Beside the TS table top systems the modular and expandable AVI series enables an individual adaptation to any application that comes with different dimensions and design. The units of the AVI-series are available as single units (AVI350), double units (AVI400) und triple units (AVI600). The minimum configuration consists of two units and can be expanded. It is even possible to use single-, double-, and triple units together in one system.

<table>
<thead>
<tr>
<th>Model</th>
<th>Dimensions (single unit)</th>
<th>Max. load</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVI350S/LP</td>
<td>360 x 92 x 111 mm³</td>
<td>2 x 200 kg</td>
</tr>
<tr>
<td>AVI350M/LP</td>
<td>600 x 92 x 111 mm³</td>
<td>2 x 200 kg</td>
</tr>
<tr>
<td>AVI400S/LP</td>
<td>360 x 190 x 113 mm³</td>
<td>2 x 400 kg</td>
</tr>
<tr>
<td>AVI400M/LP</td>
<td>720 x 190 x 115 mm³</td>
<td>2 x 450 kg</td>
</tr>
<tr>
<td>AVI400EM/LP</td>
<td>750 x 190 x 118 mm³</td>
<td>2 x 450 kg</td>
</tr>
<tr>
<td>AVI600S/LP</td>
<td>360 x 288 x 113 mm³</td>
<td>2 x 600 kg</td>
</tr>
<tr>
<td>AVI600M/LP</td>
<td>720 x 288 x 115 mm³</td>
<td>2 x 600 kg</td>
</tr>
</tbody>
</table>

key applications:
- Scanning Electron Microscopy (SEM & FIB)
- Transmission Electron Microscopy (TEM)
- Scanning Tunnel Microscopy (z.B. Cryogenic STM)
- Interferometry & wafer inspections systems
- Stationary surface roughness measuring station
- Nanolithography & Nanoengineering
10. Vibration analysis (on-site)

Sometimes it is helpful to measure the disturbing vibrations on-site to get local information about room condition, vibration sources, and dimensions. Moreover, vibration effects can be separated from acoustic and electromagnetic influences.

Three different main influences can occur:

- disturbances by vibrations
- acoustic influences
- electromagnetic induction

The vibration analysis displays the spectral distribution and amplitude. The room conditions can be quantified.

HWL offers vibration analysis as an addition service:

It consists of:

1. Measurement of the on-site condition regarding vibrations:
   - periodic disturbances (steady state) (e.g. motors and pumps that runs constantly)
   - splicing (e.g. pressing plant)
   - random vibrations (e.g. traffic and temporary used machines)

2. Spectral analysis of the recorded data:
   - Power Spectral Density PSD
   - Power Spectrum
   - FFT Spectrum
   - Measurement of the velocity (optional acceleration & displacement possible)
3. Creation of a detailed measuring report including recorded data and evaluation

The vibration of all 3 room directions will be detected simultaneously but independent. Quick scans (within seconds) realises the detection of the vibration spectra. This is the mostly used method. Moreover, long term measurements are also possible to detect stochastic resp. non-periodic disturbing sources.

**Short explanation of the different algorithm:**

**Power spectrum**

Most requested analysis method. The power spectrum includes periodic vibration disturbances and displays the energy per frequency (analogue: kinetic energy \(\sim v^2\)). The unit is \((\text{signal})^2\) and the square root of it will be displayed. The units of the ordinate are typically: velocity \([\mu\text{m/s}]\), displacement \([\mu\text{m}]\) or acceleration \([\mu\text{m/s}^2]\).

**Power Spectral Density (PSD):**

In contrast to Power Spectrum the PSD includes periodic and stochastic disturbances. The Power Spectral Density displaces the energy of vibration in an infinite frequency range. The integration over all frequencies is equal to the total power. The PSD displays the energy distribution per frequency of the detected vibrations. The unit is \((\text{signal})^2/\text{Hz}\) the often the square root of it will be displayed. It is very useful to measure the vibration in the velocity mode as the sensitivity of the signal is hardly constant within the frequency range of 0-500 Hz.

**FFT spectrum**

The disadvantage of the pure FFT-signal is due to the dependent signal-noise ratio based on the quantity of the detected data. The more data will be used for the FFT transformation the better the signal-noise ratio. However, the noise is important for the evaluation of the existing vibrations. Therefore, the Power Spectrum or the PSD will be mainly used.

**Relation between displacement, velocity, and acceleration in case of harmonic signals:**

The displacement can be easily calculated from the velocity at harmonic signals. Measuring the displacement directly in the displacement mode leads to a high signal sensitivity at lower frequencies (<50 Hz) but this detection method unfortunately comes with a less sensitivity at higher frequencies (>100 Hz). Vice versa the direct detection of the acceleration in the acceleration Mode comes with less sensitivity at lower frequencies and better sensitivity at higher frequencies. Using the Power Spectrum for the analysis displacement and acceleration can be calculated from the detected velocity.

**Mathematical relations:**

- Displacement \([\mu\text{m}]\) = velocity \([\mu\text{m/s}]\) / (2·π · frequency [Hz])
- Acceleration \([\mu\text{m/s}^2]\) = velocity \([\mu\text{m/s}]\) · (2·π · frequency [Hz])
- Peak (0-Pk) = \(\sqrt{2} \cdot \text{RMS}\) (root mean square)
- Peak to Peak (Pk-Pk) = 2 · Peak (0-Pk)
11. Analysis example

**not isolated:**
The vibration will be detected over the whole frequency range.

**passive isolated:**
Vibrations >30Hz will be passive isolated well. However, passive dampers come to their limit at lower frequencies. System relevant natural resonances even amplifies the occurred vibrations.

*Please notice the different ordinate scaling !!!*

**aktive isolated:**
Dynamic controlled feedback systems (e.g. AVI&TS-series) are free of any low frequency resonance and isolates very effective even at very low frequencies.

Response: <10 ms
Literature:

    Birkhäuser, Basel, 1997

    Ernst & -Sohn, Berlin, 2007

[3] *VDI – Richtlinien (VDI 2064 - Entwurf)*

HWL Scientific Instruments GmbH
Georgstrasse 11
72119 Ammerbuch
Germany
www.hwlscientific.com