White paper

“Semiconductor Machines: active isolation system for process stability and throughput enhancement”

Keywords:
acceleration feedforward, active isolation system, drive force cancellation, feedback path, feedforward accuracy, floor quality, floor vibration, jitter, move and settle time, passive isolation system, position stability, process stability, relative versus absolute sensing, signal to noise ratio, skyhook damping, stage sensitivity, throughput enhancement, transmissibility curve.

Abstract

The purpose of this white paper is to describe how the active vibration isolation solution developed by ETEL S.A. can guarantee a high process stability as well as an increased throughput in semiconductor applications.

Introduction

The semiconductor market is driven by key parameters such as reliability, time to market and Costs of Ownership (CoO). The latter is in direct relation to machine throughput, precision, and yield.

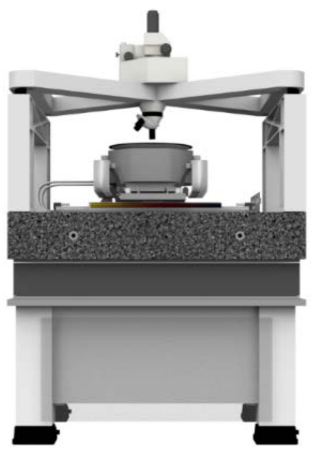

Fig.1 Typical machine architecture.

Semiconductor tools are most of the time based on a very similar mechanical architecture. A process plate holding a processing tool, a motion system holding the substrate to be treated, both connected to a granite, sitting itself on a damping system, all this connected to the floor through a frame (Fig.1).
When it comes to applications requiring high throughput together with high process stability, the isolation system becomes of utmost importance.

The main goals of an isolation system are to:
(1) filter out the vibrations coming from the floor, (2) cancel the driving forces generated by the movement of the stage itself.

Coping with (1) can be done with a pure passive system to a certain level, while coping with (2) at the same time involves either an alternative motion system architecture (balanced mass) or the use of an active isolation system.

Until now, Original Equipment Manufacturers (OEM) had no choice but to combine on their own the motion system, the motion control and the vibration isolation system. One commonly agreed limitation of this approach relates to the management of too many different suppliers, no one getting clearly the ownership of the overall machine performance.

One supplier in the motion system world is now capable of taking up this challenge. As part of its *“Forward Integration”* strategy, ETEL S.A. developed its own active vibration isolation solution bringing the company as the motion system supplier with the largest scope of supply in the world (Fig.2).

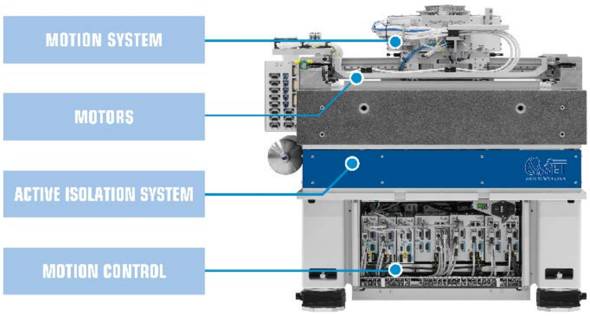

Fig.2 ETEL as a global supplier.

QuiET is ETEL's answer to the vibration isolation challenge. This platform allows to cope with both ground-born and stage-born vibration sources.
This white paper discuss about isolation systems in general and active isolation system in particular, highlighting the QuiET advantages in details.

Main reason calling for an isolation system

The primary reason to implement an isolation system in a tool relates to the floor vibration level resulting in lousy position jitter of the substrate that is affecting the process stability.
In some other applications, throughput enhancement and thus move and settle time improvements require drive force cancellation that can only be carried out through a certain category of isolation system.

Floor disturbance sources

There are mainly two sources of disturbances that have to be considered in a machine environment: the *external* source of vibrations (basically the vibrations coming from the floor) and the *internal* source of vibrations referring to disturbances coming from the movement of the motion system itself.

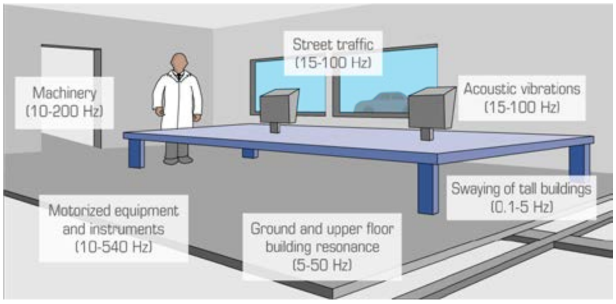

Fig.3 Environmental vibration sources.

Floor vibrations are linked to many different sources as shown in Fig.3. Each of them being active within a typical frequency range. All those vibrations can at some point "disturb" the piece of equipment sitting on the machine base, deteriorating the overall machine performance.

Floor quality must be considered as one key contributor to the final machine performances.

Floor quality metrics

The quality of a floor is usually defined following a commonly used and specific norm, called the "VC" norm and shown in Fig.4.

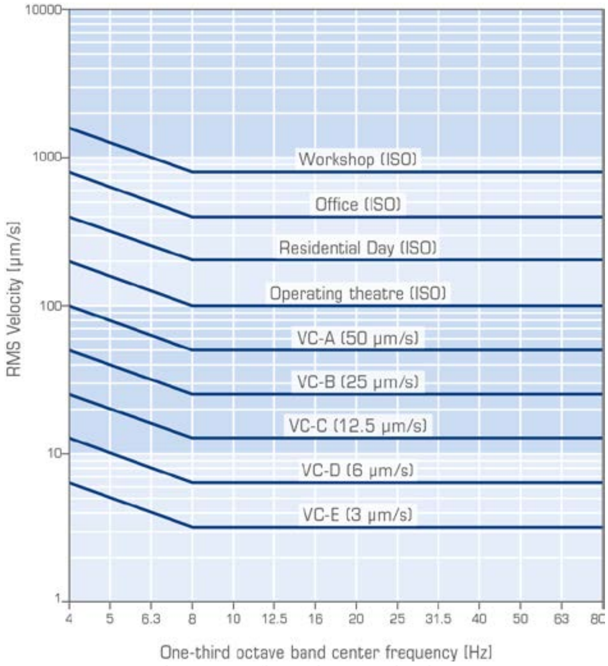

Fig.4 VC-x floor characterization.

The VC norm defines different levels of vibration VC-A, VC-B, VC-C, VC-D and VC-E. It is expressed as a speed and given as a function of the frequency.

Practically speaking, the different levels shown on Fig.4 are summarized in Table 1.

VC-A	No vibration felt. Minimal audible noise for environmental control equipment. Adequate in most instances for sensitive equipment and applications including optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, optical trapping, fluid dynamics, and high-resolution laser imaging.
VC-B	No vibration felt and less than 40 dB audible noise. An appropriate standard for optical microscopes to 1000X, inspection and lithography equipment (including steppers) to 3 µm linewidths.
VC-C	No vibration and less than 25 dB audible noise. A good standard for most lithography and inspection equipment to 1 µm detail size.

VC-D	No vibration felt and less than 15 dB audible noise. Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems, operation to the limits of their capacity.
VC-E	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, and other systems.

Table 1 VC-x levels of vibration.

Passive versus active isolation systems

When an object has to be isolated from floor vibrations, two options can be foreseen: *passive damping* or *active damping*. In a nutshell, the characteristics of each can be summarized as follows:

A **passive isolation system** consists of a spring and damper. The spring is intended to isolate from the floor vibrations, while the damper is damping the natural frequency of the mass/spring system.
The isolator can also be of different types: air bladder, foam, magnetic elements.
The passive damping element can be hydraulic, pneumatic or made up of polymer.

In an **active isolation system**, the system is also sitting on a spring or equivalent but there is a sensor used to measure the vibration. This information is fed to an actively driven damper which can be a linear motor, a pneumatic cylinder, or a hydraulic cylinder. Active isolation system enables a higher degree of vibration isolation compared to a passive one.

Relative versus absolute damping

Depending on the architecture that is chosen, two different types of damping can be defined referred as to *relative* or *absolute* damping.

Relative damping

In a system providing a *relative* damping (active or passive), both isolator and damper are connected between the moving body and the ground.

Relative and passive damping system

This is the typical configuration of a car driven on a bumpy road. It is a relative and passive damping system (Fig.5).

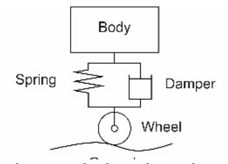

Fig.5 Relative damping system, passive.

Relative and active damping system

Fig.6 shows a relative measurement applied to a motion system sitting on an active damping system.

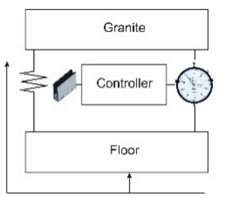

Fig.6 Relative active damping system.

Absolute damping

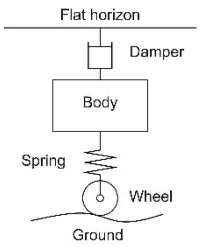

Fig.7 Absolute passive damping system.

In a system providing an absolute damping, the isolator connects the moving body to the ground and the damper connects the moving body to an absolute and fixed reference. The measurement is taken from the body to this absolute reference.
This is shown in Fig.7 and 8. The absolute reference could be taken as a geostationary satellite. The satellite is not moving, unlike the ground.

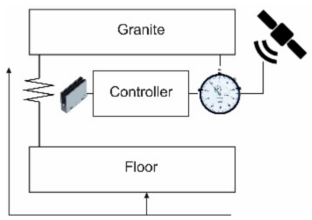

Fig.8 Absolute Active damping System.

When comparing two active isolation systems, the sensor used for measurement will make the system relative or absolute. As shown later in Fig.24, the isolation performance level is better with an absolute damping system than with a relative one, active or passive.

Transmissibility performance

To qualify the performance of an isolation system, the key parameter is the *Transmissibility*.

The transmissibility (Fig.9) is a ratio between the vibration of the floor (XFloor) and the vibration of the granite (XGranite) that is sitting on the isolation system.

$$Transmissibility = \frac{XGranite}{XFloor} \qquad (1)$$

This ratio gives the amplification or reduction factor between the output (here the granite displacement) and the input (here the floor displacement).

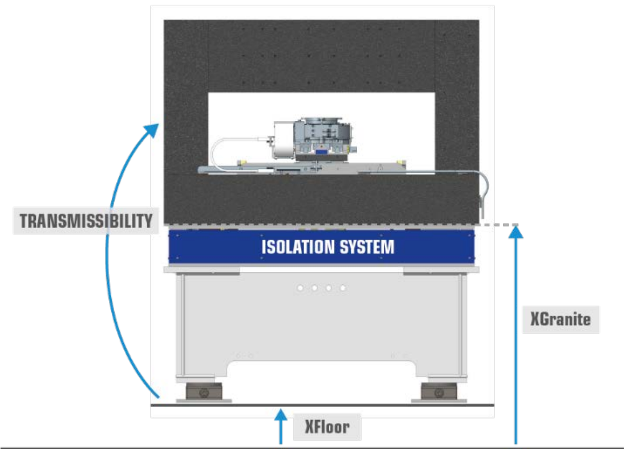

Fig.9 Transmissibility.

Transmissibility curve

The transmissibility curve provides the vibration isolation capability as a function of the frequency of the floor vibrations. It is given in a Bode plot showing a gain (in dB) as a function of frequency (in Hz), as shown in Fig. 10.

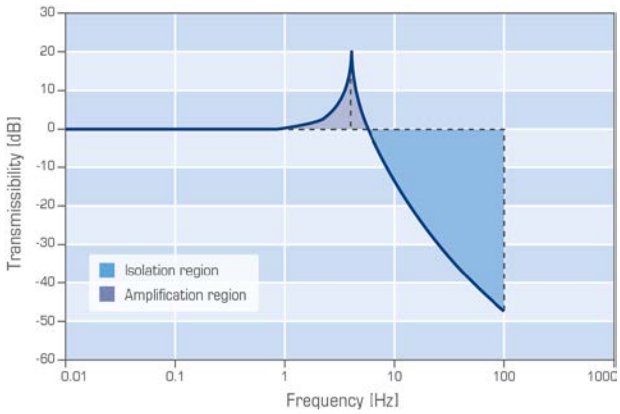

Fig.10 Transmissibility curve.

In Fig.10, an amplification of vibrations between 1 and 8 Hz and a reduction of vibrations from 8 Hz and above can be seen.

The peak in the amplification region typically corresponds to the natural frequency of the isolator.

Reading a transmissibility curve

When reading a transmissibility curve, the units along the X axis are provided on a logarithmic scale in Hz. The slope of the transmissibility curve is given in dB/decade.

Typically, a mass-spring system is an isolator that has a -40dB/decade isolation capability at high frequency (Fig.11).

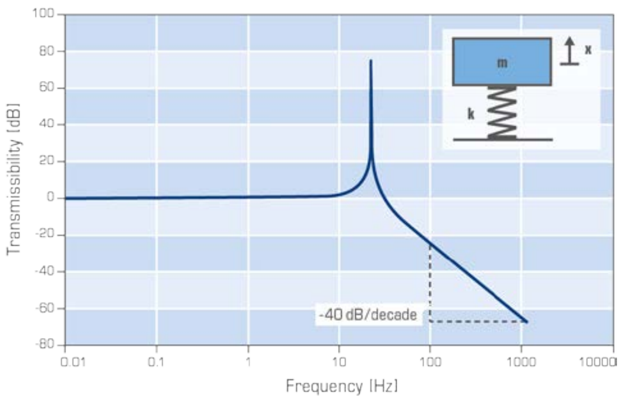

Fig.11 Mass-spring transmissibility curve.

Converting dB in a damping efficiency

The dB is a logarithmic way to describe a ratio.

Converting a gain given in dB into a ratio is done with the following formula:

$$Gain\ (dB) = 20 \times \log \frac{Output}{Input} \qquad (2)$$

or

$$\frac{Output}{Input} = 10^{\left(\frac{Gain}{20}\right)} \qquad (3)$$

For example, this means that:

- -10 dB translates into a ratio of 3 between the input signal and output signal.
- -20 dB translates into a ratio of 10 between the input signal and output signal.
- -40 dB translates into a ratio of 100 between the input signal and output signal.

Stage sensitivity - Control bandwidth

A motion system has some capability to reject an external disturbance through its position feedback and control loop. The rejection is usually extremely good up to the stage control bandwidth and degrades heavily above it.

This rejecting capability is called "Sensitivity" of the stage. Similarly to the transmissibility curve that can be plotted for an isolation system, a sensitivity curve can be plotted as a function of the frequency for the capacity of the stage to reject a given perturbation.

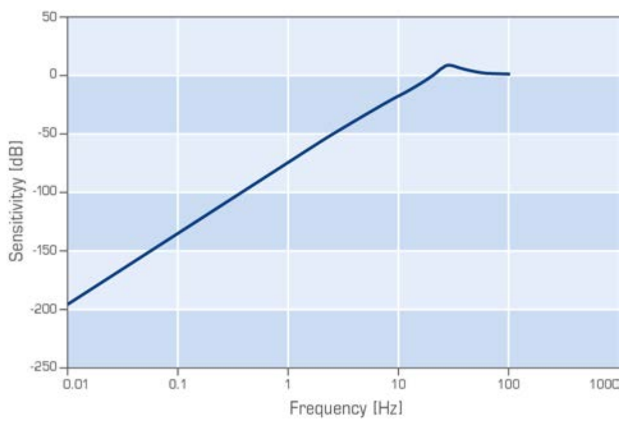

Fig.12 Typical stage sensitivity.

Ultimately, the position stability that can be reached on a motion system platform is a combination of the sensitivity of the stage itself and the vibration level of the granite it is sitting on.

Machine environment

Assuming a floor considered as infinitely stiff and with an infinite mass, all vibrations are directly transmitted to the granite without attenuation. The transmissibility is 1, or 0 dB (Fig.13).

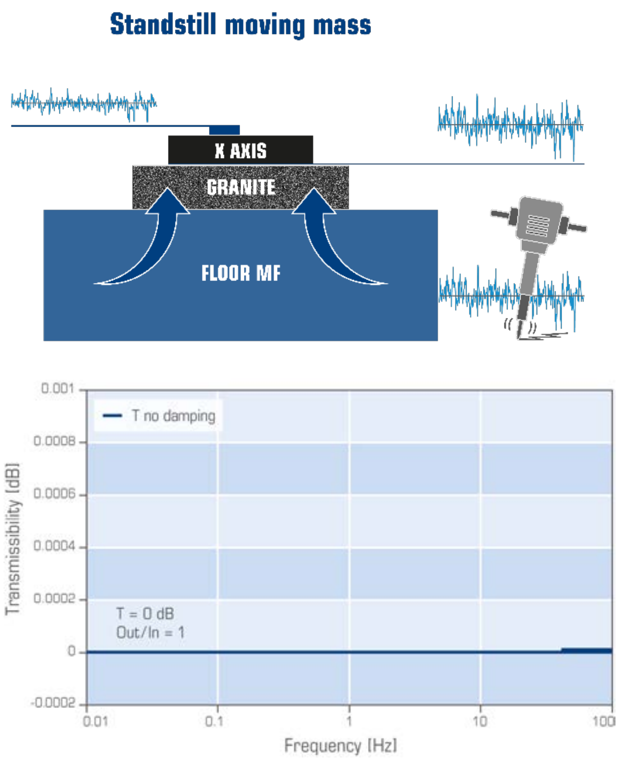

Fig.13 Infinite stiffness connection to the floor.

Considering the motion system sensitivity (Fig.12), part of the perturbation of the granite will be filtered out at the motion stage level.

In this configuration, when the stage is moving, generating driving forces, the reaction forces on the floor lead to no perturbation because of the stiff connection and the infinite mass of the floor itself. Move and settle times are therefore not affected by the link to the floor.

The vibrations at the stage level being attenuated by the sensitivity of the stage, the vibrations at the granite level are now the main focus.

To avoid that the floor vibration affects the process stability, the granite has to be isolated from the floor. The very obvious and simple type of isolator is the spring, similar to the one used in cars. It could also be a piece of elastomer. A natural frequency of around 20 Hz is considered for this isolator (Fig.14).

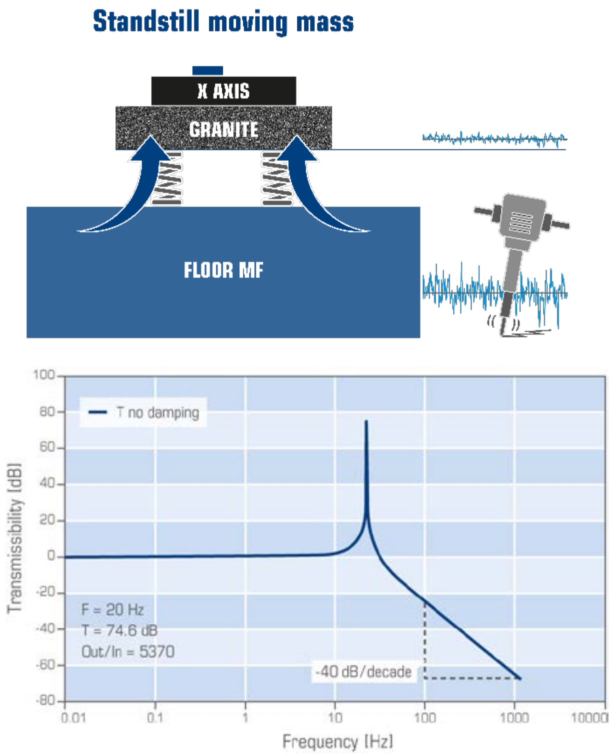

Fig.14 Spring as an isolator from floor vibrations.

At the natural frequency of the spring (here 20 Hz), there is a very large amplification of the vibration (here T=74.6 dB → Out/In= 5370 because the internal damping factor is very low).

Below this frequency (low frequency domain), the transmissibility is 0 dB, Out/in=1.

Above this frequency, the transmissibility follows a -40 dB/decade slope. In other words, isolation becomes very efficient.

The large amplification at the natural frequency of the spring is not sustainable process-wise. It needs to be damped. Assume this damping is done with a passive damper like an elastomer, an air bladder, a pneumatic or hydraulic damper, etc.

In this configuration, the transmissibility plot becomes the light blue curve in Fig.15.

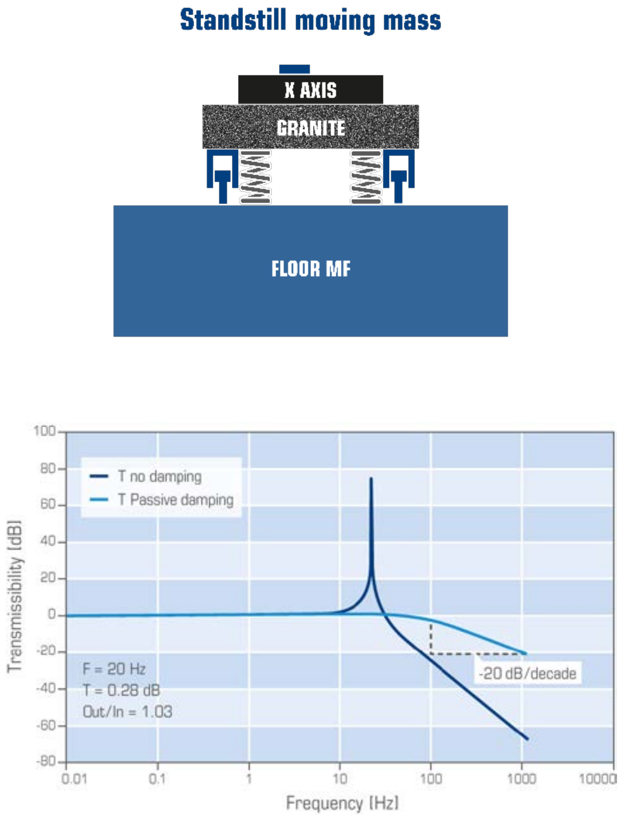

Fig.15 Passive damper.

The amplification at the natural frequency of the spring is largely attenuated. Here, transmissibility at 20 Hz is down to 0.28 dB (Out/In=1.03).

Due to the fact that by design, a passive damping system is relative and difficult to make absolute, it can be seen that the slope beyond the natural frequency of the oscillator has changed from -40 dB/decade to -20 dB/decade.

In other words, adding a passive damper to build a passive relative isolation system improves the isolation around the natural frequency of the mass/spring and deteriorates the damping capability at higher frequency. In this configuration, the higher is the damping around the natural frequency, the lower is the transmissibility curve slope at higher frequency.

There is a way to improve the damping capability at high frequency while isolating properly around the natural frequency of the spring. This is possible by using an *absolute active isolation system*.

The active damping part can be done through an electrical actuator, typically linear motors.

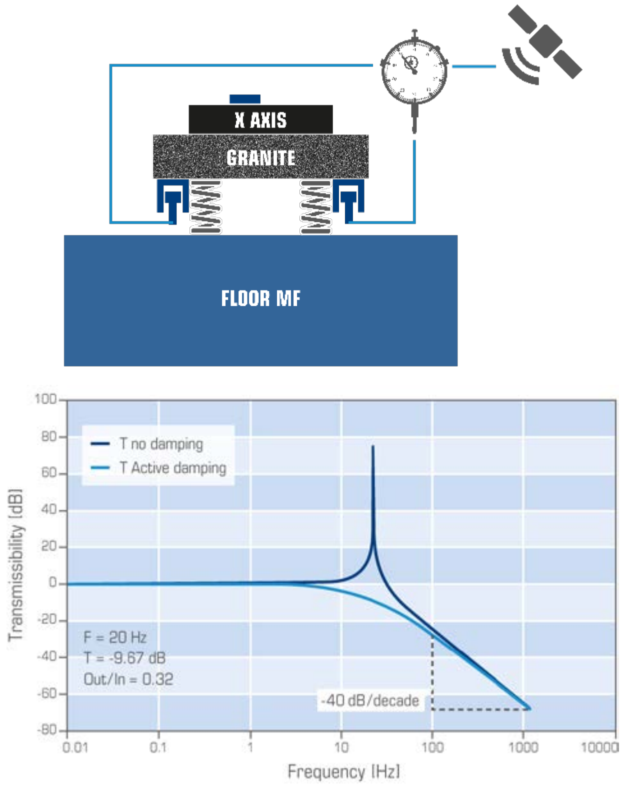

Fig.16 Absolute active damping system.

An absolute active isolation system brings at the same time an improvement of the isolation around the natural frequency of the spring (here T=-9.67 dB or out/in=0.32) and a better damping capability at higher frequency than a passive one (-40 dB/decade versus -20 dB/decade), as shown in Fig.16.

In the example before, the natural frequency of the isolator was selected at around 20 Hz.

In Fig.17, the impact of the natural frequency selection on the isolation capability of the system can be seen. The lower the natural frequency, the better the isolation capability.

In light red, the transmissibility curve of a mass on spring system where the natural frequency of the spring is 8 Hz.

In plain red, the transmissibility curve of an active absolute damping system with 8 Hz spring.

In light blue, the transmissibility curve of a mass on spring system where the natural frequency of the spring is 4 Hz.

In plain blue, the transmissibility curve of an active absolute damping system with 4 Hz spring.

At a frequency of 100 Hz, the isolation capability of a system with a 4 Hz spring has a transmissibility of about -58 dB while it is about -43 dB for an 8 Hz spring. The 15 dB difference leads to a better attenuation of 15 dB which means a factor of 5.6 ($10^{15/20} = 5.6$).

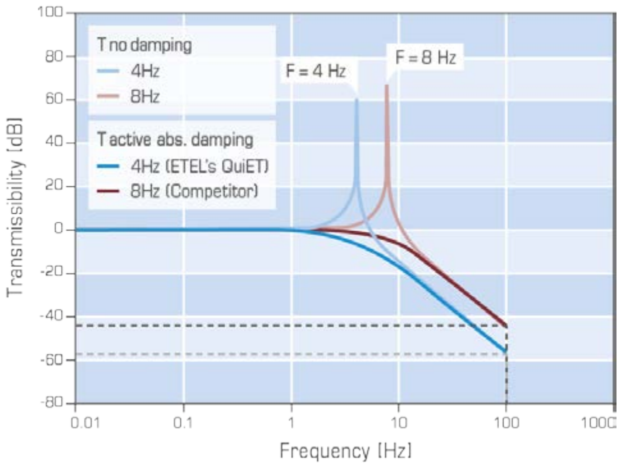

Fig.17 Isolation capabilities as a function of isolator natural frequency.

Drive forces disturbance induced by the motion system

The second source of vibration is inherent to the movement of the motion system itself. Now that the granite is sitting on spring and damper, it is well isolated from floor vibrations.

Every time a movement is performed on a stage, a given moving mass is accelerated and decelerated.

Following the Newton's law, these acceleration/deceleration generate "driving forces" that are directly transmitted to the base (granite or other) it is sitting on. The granite being "hit" by these forces, some vibrations are taking place at the granite level, affecting the stability of the process tool sitting on it (Fig.19).

This is where the active dampers bring another key differentiator compared to the passive ones.

Active dampers can counteract this "rocking" effect by injecting the right amount of current in the motors to cancel out the driving forces. This has a direct impact on the move and settle times that can be expected at the process level.

This is typically referred as to *"acceleration feedforward".*

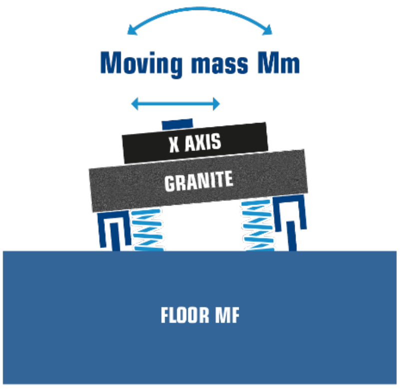

Fig. 18 Drive Force Cancellation.

Drive force cancellation

The drive force cancellation consists in counteracting the driving forces generated by the motion of the system (in red in Fig.19) by applying forces of the same amplitude but opposite directions (in green in Fig.19). The sum of all forces is then equal to zero at the granite level.

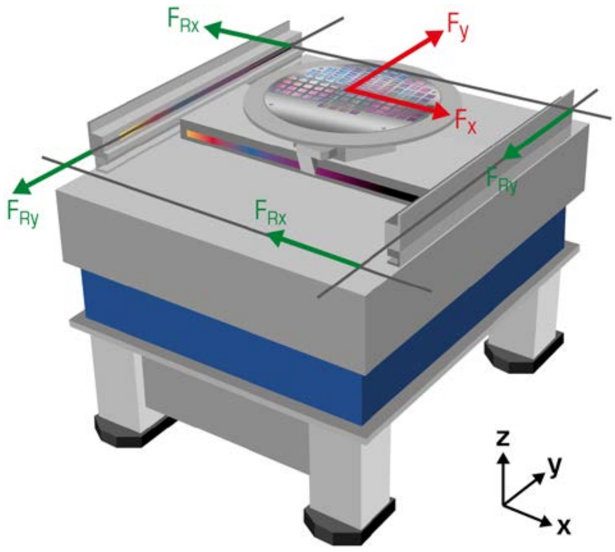

Fig.19 Driving force cancellation in XY plane.

This is true as long as all motors, from both the motion system and reaction frame are acting perfectly in the same plane.

Unfortunately, this is never the case in real life, when considering the final integration done by the OEM. For instance, the center of gravity of the load and the load itself might be changing after customer chuck integration or even in the course of the process itself. Therefore, the best compromise is to have all the reaction motors and associated sensors located into a single box located under the granite of the motion system. By lowering the force plane of the reaction motors, they also have to compensate Mx and My moments, in addition to the forces in X and Y directions. This is possible through additional linear motors acting along the vertical direction as shown in Fig.20.

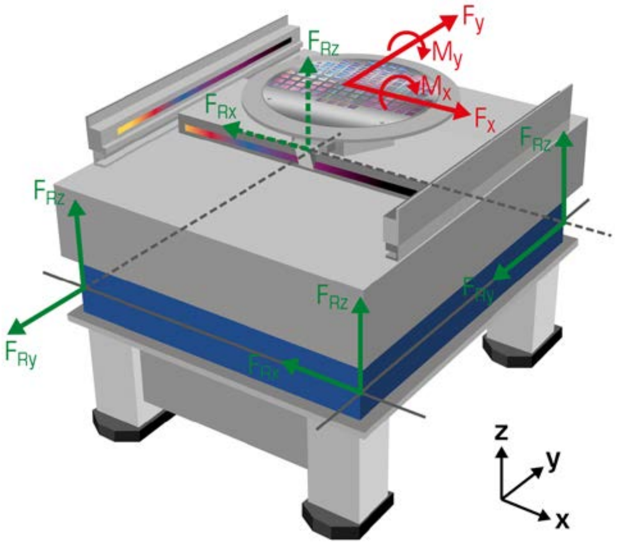

Fig.20 Driving force cancellation in XYZ.

Feedforward path

To have a perfect cancellation of the forces (red versus green), the proper information of moving mass, center of gravity and acceleration at the stage level must be transmitted to the controllers of the active isolation system. This data transmission must be done as fast as possible and correctly synchronized to avoid any delay in the "counteracting action". This is called the *"feedforward path"*.

The feedforward accuracy is then defined as the percentage of the driving force that is cancelled by the active isolation system.

The communication bus between the different sets of controllers (for the motion system and for the active isolation system) plays a key role here. In most of the conventional configurations, the connecting bus is analog, ±10V, and the resulting Driving Force Cancellation (DFC) is in the range of 80 to 85%.

With its AccurET controllers and TransnET communication bus, ETEL offers a purely digital, fully deterministic and synchronized communication allowing to boost this DFC to an outstanding 99% level!

Feedback path

The remaining 1% of energy that is not cancelled by the active isolation system will be rejected by the feedback system of the active isolation platform.

ETEL's QuiET system

QuiET is the active isolation product of ETEL.

QuiET can be used with any type of motion systems.

It is a 6 Degrees Of Freedom platform of a "sandwich type". It is made out of two aluminum plates connecting the frame on one side and supporting the motion system on the other one.

Fig.21 QuiET.

All active and passive components are located in between the two plates namely: 4 isolators (springs), 6 sensors, 2 motors pushing in X direction, 2 motors pushing in Y direction, 4 motors pushing in Z direction and 3 hard stops.

The isolator module is made of a spring that is sized in terms of stiffness to cope with the given static mass. It is chosen to have its natural frequency below 5 Hz for the reasons described earlier.

The QuiET differentiates by the type of sensor that is used. Conventional solutions are using speed sensors (geophones) and acceleration sensors (accelerometers).

Both solutions reach limitations, especially at low frequencies in terms of resolution and signal to noise ratio (SNR). ETEL sensor module provides an absolute position information of the granite with a much better signal to noise ratio compared to conventional solutions.

This is helping to lower the natural frequency of the mass-spring system while further increasing the damping of it, both resulting in a better isolation capability.

Control architecture

Two AccurET VHP controllers (Fig.23) are needed to drive the 8 motor modules. Depending on the number of coils that are constituting each of the 8 motor modules, different power levels might be required on the controller side.

The UltimET motion controller used at the motion system level will also allow the perfect synchronization between the 2 controllers within 10 ns.

Power supplies are shared between controllers of the motion system and controllers of the QuiET.

QuiET - Key performance – Unique selling points

Outstanding isolation from floor vibration – Transmissibility performance

The QuiET active isolation system is equipped with a 4Hz natural frequency spring. Its typical transmissibility curve is shown in Fig.22.
with a -40dB/decade damping from 4 Hz on.

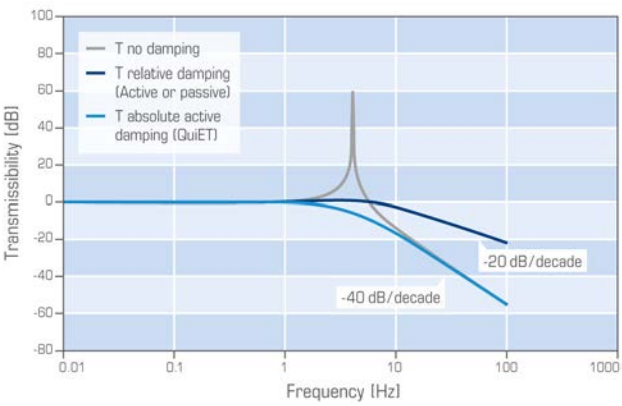

Fig.22 QuiET transmissibility curves - Active versus passive.

Comparing QuiET transmissibility curve with passive one, a factor of 2 can be observed between the slopes at high frequencies which translates into the following typical damping factors:

- $@10\ Hz, passive: \frac{Output}{Input} = 10^{(\frac{Gain}{20})}$ → $10^{-0.5/20}$ = 0.944
- $@10\ Hz, active: \frac{Output}{Input} = 10^{(\frac{Gain}{20})}$ → $10^{-20/20}$ = 0.1
- $@50\ Hz, passive: \frac{Output}{Input} = 10^{(\frac{Gain}{20})}$ → $10^{-17/20}$ = 0.141
- $@50\ Hz, active: \frac{Output}{Input} = 10^{(\frac{Gain}{20})}$ → $10^{-42/20}$ = 0.0079

To summarize, comparing the QuiET active isolation system from ETEL to a passive one, vibrations are:

- 10x better damped at 10 Hz
- 18x better damped at 50 Hz

QuiET - 99% Cancellation of driving force - Acceleration feedforward accuracy performance

ETEL QuiET solution allows an outstanding Drive Force Cancellation thanks to the electronics architecture and thanks to the TransnET real time communication between the motion system controllers and the QuiET controllers.
Through the *Forward Integration Concept* of ETEL providing automatic algorithm for QuiET auto-tuning, a 99% force cancellation can be reached depending on the frequencies we are looking at. This means that only 1% of the energy generated by the stage movement remains at the granite level!

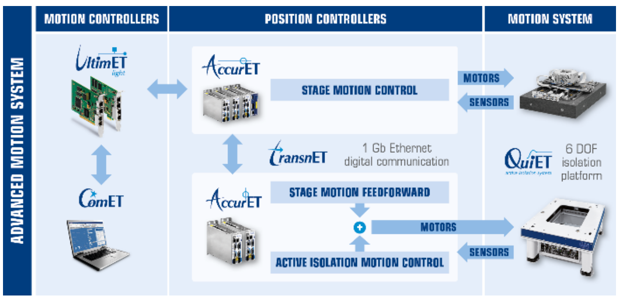

Fig.23 Shared motion system and QuiET control architecture.

Drive force cancellation of multiple yet independent moving stages

The QuiET control architecture allows to cope with the drive force cancellation of several independent axes moving simultaneously on the same granite base. This can for example serve machines integrating two independent XYZ stages or independent rotary axis.

Active Isolation system performance – QuiET versus competition

In light of what has been discussed above, two parameters are key when trying to compare different isolation systems:

1. The transmissibility curve
2. The feedforward accuracy

Those two points are key differentiators of QuiET versus competitor's products.

As shown in Fig.24, QuiET demonstrates a better filtering of floor vibrations which translates into better position stability at the process level and better uniformity of this position stability over the full working area.

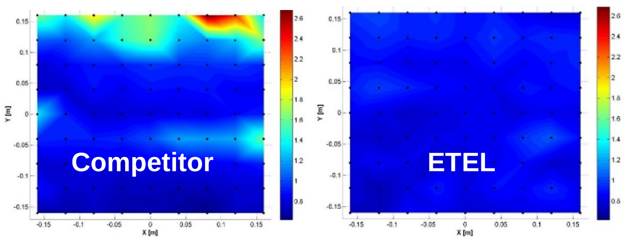

Fig.24 Nanometer position stability.

Because the natural frequency of QuiET spring is very low (4Hz in Fig.17), isolation at high frequency is better than an equivalent system based on springs with higher natural frequency (8 Hz in Fig.17).

A shown in Fig.25, QuiET also demonstrates better acceleration feedforward accuracy which leads to shorter move and settle times.

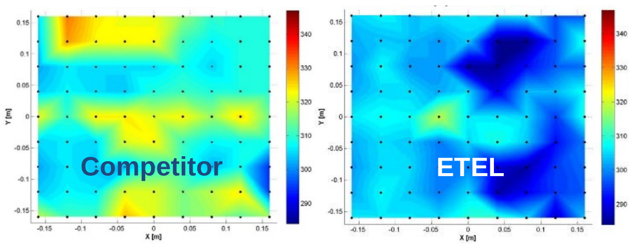

Fig.25 Move and Settle time enhancement – 25 mm typical move, identical motion system.

Why buying an ETEL QuiET isolation system?

As described in this paper, ETEL's QuiET offers:

- A state-of-the-art 6DOF active isolation system
- A transmissibility of -40 dB/decade from 4 Hz on
- A control architecture allowing to reach up to 99% feedforward accuracy
- An ability to deal with several groups of different motion systems on the same base
- A compatibility with any type and brand of motion systems
- A unique opportunity to reduce supplier management costs, as well as logistics and integration costs by having ETEL as the unique supplier of the comprehensive motion system solution including the motion system, the control electronics, and the active isolation system

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