EQUALIZER: REDUCING VIBRATIONS, PRESERVING STIFFNESS

A novel tool to reach low vibration levels in existing buildings has been developed. Active vibration cancellation can be applied on floors in existing buildings next to already installed equipment. A few sensors and actuators the size of a shoe box together with a control system can lower vibrations with a factor three to ten. The lower vibration levels do not come at the cost of lower stiffness as is the case with active or passive isolation solutions.

SERVAAS BANK

A quiet place

With the demand for ever smaller structures there is an increasing demand for a quiet place within precision machines, where accurate processes are not hindered by vibrations. In practice the precision machine has a vibration specification, the maximum vibration level at which it will achieve its intended performance. The user has a floor where he wants to put the machine. The vibration level of the floor is measured and if it exceeds the specification a solution must be found. An isolation pedestal, which isolates the precision machine from the vibrating floor may be considered as a solution (see the first box: Non-technical aspects).

Two possible downsides to this solution however exist. Firstly, vibration isolation often does not work well underneath precision machines with internal vibration isolation, as unwanted interaction may occur, leading to increased vibration levels or decreased stability. Secondly, if the machine exerts forces on the system, which is the case for most machines with fast moving parts, the machine will need a solid, stiff support. This contradicts with an isolation solution that tends to be rather soft, even the so-called 'hard-mount' systems (see the second box: Stiffness versus isolation).

1 *Equalizers in a cleanroom. The units each measure 350 x 150 x 160 mm^3 and their mass is approx. 25 kg.*

2 *Typical situation of a factory floor with precision machine and disturbance sources.*

2 *Equalizer reducing vibrations on the floor field.*

Non-technical aspects

In case of problems, try to solve them at the source. This is a very broad and true recommendation. It holds perfectly for vibration problems. And yet, the question "we have a vibration problem – can you please solve this for me at the source?" seldom reaches the vibration expert. Most of the time the customer with the problem specifically asks for a solution at the machine.

Mecal's experience confirms the power of problem solving at the source. Sometimes a ten-minute walk through the servicing room with the proper measurement equipment and expertise can pinpoint the pumps which are causing the high vibration levels. Servicing these pumps will not only lower the vibration levels of the whole building but probably also extend the lifetime of the pumps.

Why then do customers ask for a solution at the machine? The answer lies in organisational and practical reasons. The person with the vibration problem is responsible for the precision machine, not for the building and not for the unbalanced pumps in the basement; this person wants a solution that is within his jurisdiction.

AUTHOR'S NOTE

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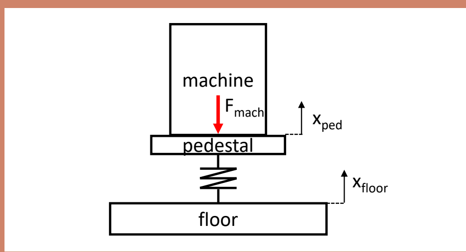
Stiffness versus isolation

Pedestal vibrations can originate from floor vibrations (x_{floor}) or from machine forces (F_{mach}). We can describe the pedestal as a simple spring mass system.



Vibrations due to machine forces

For forces of the machine applying Newton's laws leads to:

$$\text{Compliance} = x_{ped} / F_{mach} = (1/k) / (1 - f^2/f_0^2 + i \cdot 2 \cdot \beta \cdot f/f_0)$$

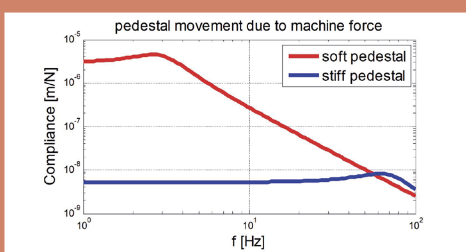
or:

$$\text{Stiffness} = F_{mach} / x_{ped} = k \cdot (1 - f^2/f_0^2 + i \cdot 2 \cdot \beta \cdot f/f_0)$$

Here:

k = spring constant [N/m]
f_0 = resonance frequency ($1/2\pi \cdot \sqrt{(k/m)}$ [Hz])
m = mass [kg]
β = damping constant
$i = \sqrt{-1}$

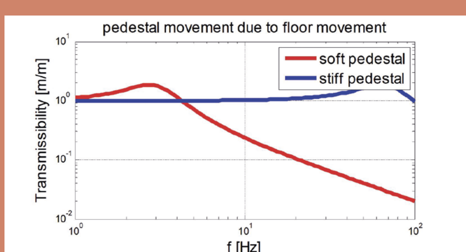
Now we can compare a 'soft' isolation pedestal with a stiff pedestal. The stiff (blue) pedestal moves much less than the isolation pedestal. Above the resonance frequency of the stiff pedestal the movement of both pedestals is governed by the mass only.

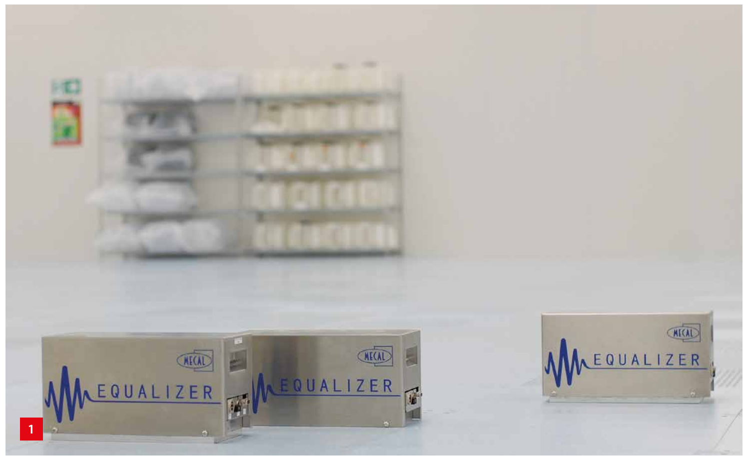


Vibrations due to floor movement

$$\text{Transmissibility} = x_{ped} / x_{floor}$$
$$= (1 + i \cdot 2 \cdot \beta \cdot f/f_0) / (1 - f^2/f_0^2 + i \cdot 2 \cdot \beta \cdot f/f_0)$$

We can plot this for the same soft and stiff pedestal. The soft (red) isolation pedestal moves less than the stiff pedestal. Active vibration cancellation with an Equalizer gives the opportunity to have the robustness and good performance for machine forces of a stiff pedestal and still have a significant reduction of floor vibrations.





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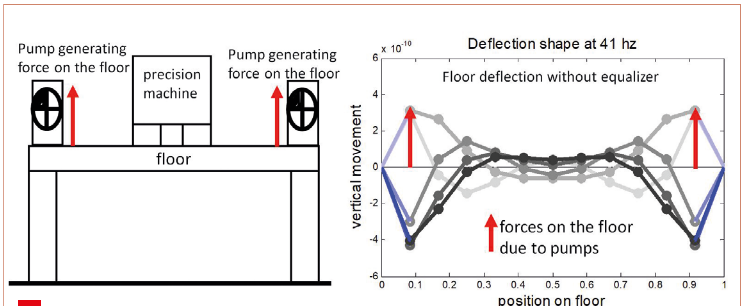
An alternative solution to lower vibration levels without lowering the stiffness beneath the machine and with little to no interaction with any active systems within the machine has been developed by Mecal. This is an active vibration cancellation system called Equalizer (Figure 1).

Working principle

Suppose a factory as in Figure 2. Disturbance sources (e.g., pumps) generate forces that lead to vibrations on the floor where the precision machine is located. In general, the floor is vertically much less stiff than horizontally and will typically have most movement in the vertical direction.

A vibration pattern with modal minima and maxima will be formed on the floor depending on the frequency of the disturbance and the modal characteristics of the



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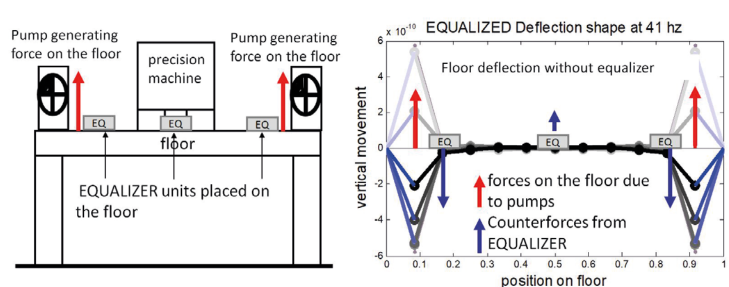

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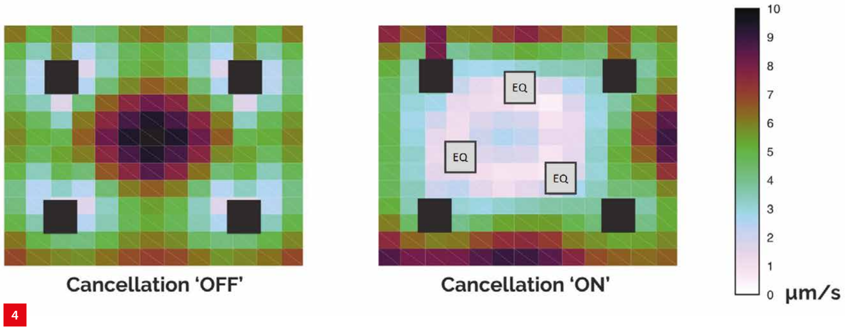

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4 *Vibration levels on a floor (left) and on the same floor with three Equalizer (EQ) units (right).*

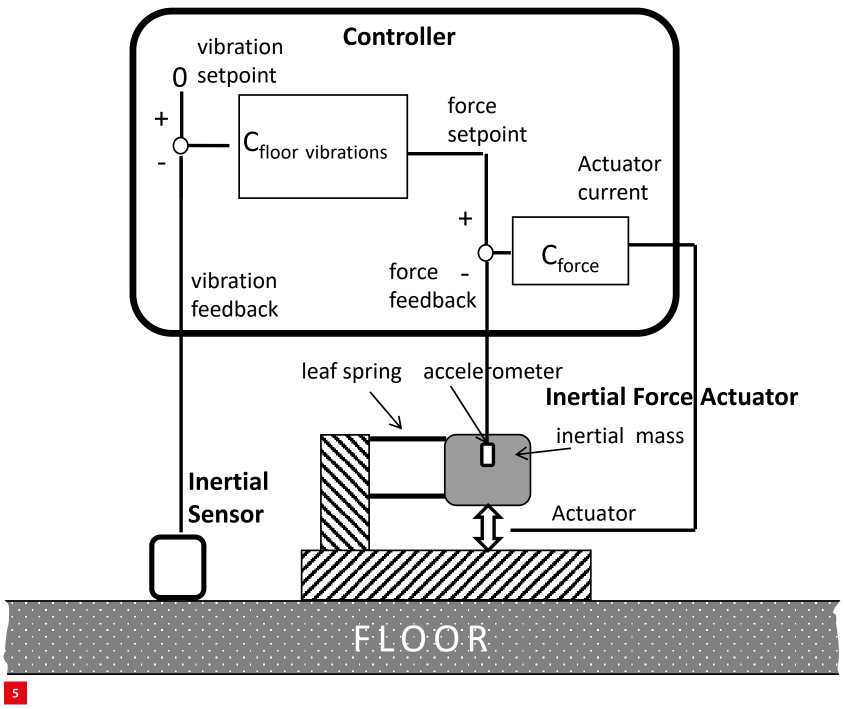
5 *Schematic of the Equalizer.*

6 *Controller and three Equalizer units.*

floor. This is indicated in the right graph of Figure 2. If the modal pattern for the disturbing frequency is known, points on the floor with a modal maximum can be selected to apply a counterforce. This counterforce will be controlled by a control system with feedback from the floor movement so that the local floor movement will be reduced with at least a factor ten. See Figure 3.

By reducing the floor movement with a factor ten at the places where an Equalizer is placed, the vibration level can be reduced over a large area with a factor three to four. An example can be seen in Figure 4, which shows a top view of a floor field. The black squares indicate the position of the supporting columns. Colour indicates the vibration levels at the disturbance frequency and the grey squares labelled EQ denote the Eequalizers.

The optimal placement of the Equalizers can be established by modal measurements of the floor and a simulation of the floor with and without the Equalizers.



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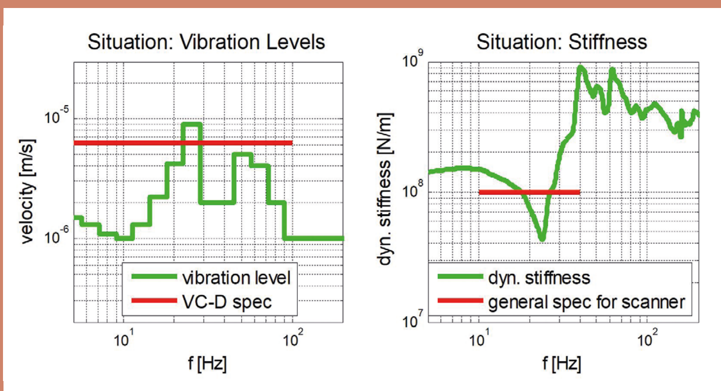
Inside the Equalizer

Each Equalizer unit consists of an inertial actuator, paired with an inertial sensor and a feedback control system (Figure 5). Based on the vibrations measured by the sensor, the control system precisely determines the force to be applied on the floor by the actuator. The feedback control loop continuously adapts the force to minimise the measured floor vibrations. It is intended to be used on the stiff fab floor or on a machine pedestal which is stiffly connected to that floor. For optimum results, usually a configuration of several Equalizer units and a controller has to be used (Figure 6).

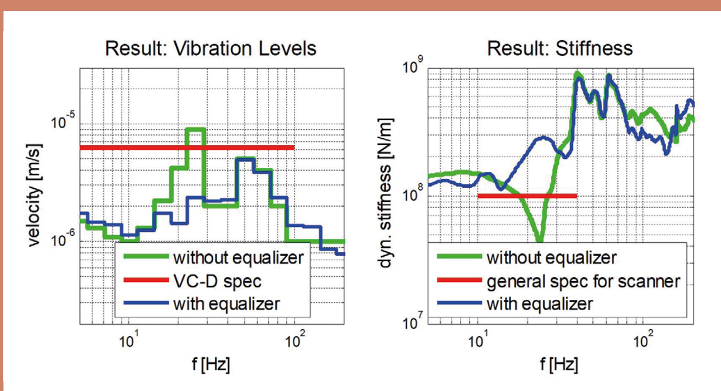
Inertial forces can be produced effectively at frequencies above the resonance frequency of the inertial mass. The lower noise limit of the system depends on the noise level of the sensor. Mecal developed an inertial sensor with noise levels well below $1 \cdot 10^{-8}$ m/s at 1 Hz (one-third octave velocity level). Subsequent internal modes of the actuator and sensor that are visible in the control loop are much higher than 500 Hz. This is necessary to achieve a controlled bandwidth up to 100 Hz.
In practice the Equalizer is most effective in cases where the vibration levels need to be lowered at one or two specific disturbance frequencies, e.g., 50 and 25 Hz, or at the frequency of a badly damped floor resonance (see the third box: Example – vibration reduction and active stiffening).

Example – vibration reduction and active stiffening

Normally, active vibration cancellation will be used to counteract vibrations with a specific frequency, e.g., 50 Hz from asynchronous motors. Because the system counteracts the forces working on the floor, it also works as an active stiffening device. This is illustrated in the graph below, which shows vibrations and stiffness measurements on a real factory floor. The vibration level exceeds the spec at 23 Hz. This is due to a floor resonance at 23 Hz indicated by a dip in stiffness where the stiffness is also below spec: the floor needs very little excitation force at this frequency to vibrate. In the graph, VC-D is a general vibration spec for demanding equipment; and $1 \cdot 10^8$ N/m is a general stiffness spec which is used for equipment with high-speed stages, like wafer scanners.



An Equalizer can be placed at this measurement point. The Equalizer control system can be tuned by a Mecal engineer at installation to be effective around 23 Hz. If the aim is a reduction of a factor 10 the results as shown in the graph below would be obtained.



The vibration peak at 23 Hz is lowered. Furthermore, the stiffness dip due to floor resonance has been effectively removed. This is not only active vibration cancellation but also active stiffening!

MECAL solving vibration problems

MECAL has extensive experience in solutions for vibration problems. This ranges from finding vibration sources, designing vibration isolation platforms and developing vibration cancellation technology, to the design-in of vibration isolation systems inside precision machines. For this, MECAL developed a wide range of technologies and competences such as Hummingbird vibration isolation technology, Equalizer vibration cancellation technology, optimised vibration sensors and model-based design and improvement of machines and buildings.

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Conclusion

Active vibration cancellation is a tool which preserves the inherent stiffness of the floor. This makes the system suitable for machines with a stiffness specification. The Equalizer system can even be used to stiffen the floor at certain frequencies. Interaction with machine dynamics or internal isolation systems is minimal since the interaction depends mainly on the floor and not on the machine.

Active vibration cancellation is a new tool for lowering floor and pedestal vibrations. Compared with traditional vibration isolation systems, whether passive or active, it has the advantage of a high stiffness and effectiveness over a large area (possibly multiple machines will benefit). In existing situations, the relative small Equalizer units can be easily placed on a few well-chosen points on the floor. Compared to high-performance active isolation, as with the Mecal Hummingbird, the vibration reduction is limited. ■