A STABLE MICROSCOPE IMAGE IN ANY BUILDING: HUMMINGBIRD 2.0

Low-frequency building vibrations can cause unacceptable image quality loss in microsurgery microscopes. The Hummingbird platform, developed earlier by MECAL, now also can serve as a vibration filter between a ceiling and a microscope. Based on a patented solution, the Hummingbird platform isolates equipment from low-frequency vibrations better than any other state-of-the-art vibration damper. As a result, the microscope user can always enjoy a stable image in any building.

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AUTHORS' NOTE

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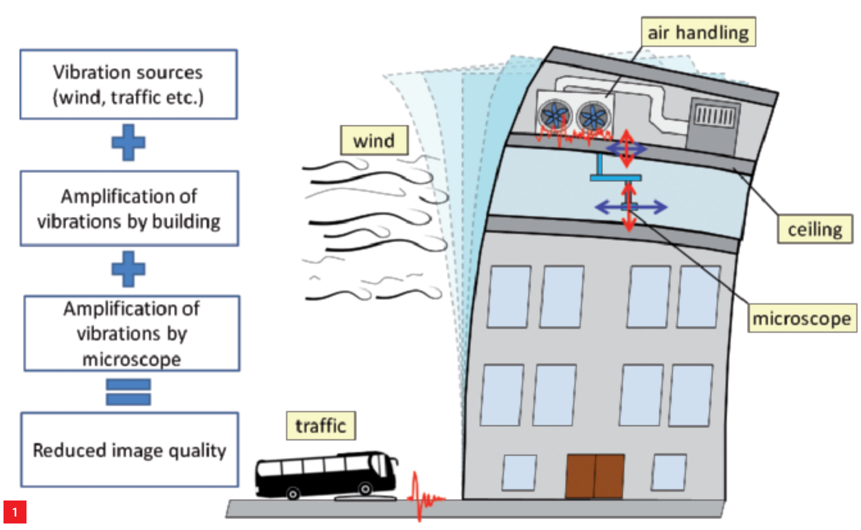
High, thin-walled buildings in glass and steel replace low and robust concrete constructions. Such modern buildings comply with all the regulations but are more sensitive to low-frequent vibrations caused by wind and traffic. These vibrations can compromise performance of sensitive equipment installed in the building. In case of microscopes used in microsurgery, this results in reduced image quality.

1 *Vibration sources.*



Introduction

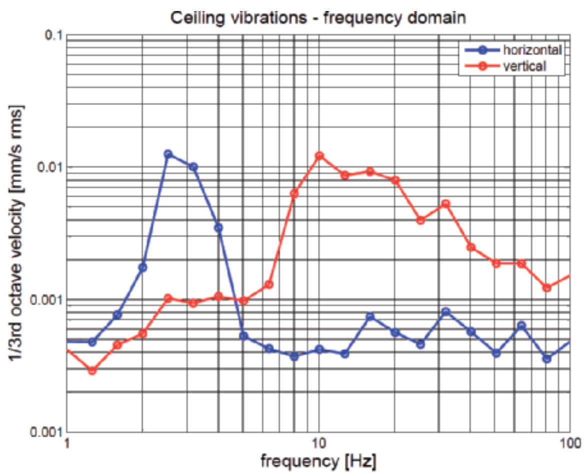
All things in life, from tectonic plates to atoms, exhibit vibrations. Some vibrations can be seen by the human eye and some can only be seen with very sensitive measurement equipment. At the academic hospital azM in Maastricht, the Netherlands, low-frequent vibrations were affecting a sensitive ceiling-mounted surgical microscope. Although the amplitude of the vibrations was about 100 times smaller than the thickness of a human hair (0.05 mm), they were visible because of the large magnification factors used in microsurgery.

Commissioned by the project office “Bouwbureau azM/RO groep” in Maastricht, MECAL investigated the case and successfully implemented a Hummingbird platform to isolate the microscope from vibrations in all directions, even at the lowest frequencies.

Investigation

In order to find the cause of the problem, vibration measurements were carried out by MECAL and by the consultancy firm Cauberg Huygen at the location of azM. These measurements showed the sources of vibration, as depicted in Figure 1:

- Traffic
  Whenever a bus drove over a speed bump nearby the building, vibrations were seen on the microscope image.



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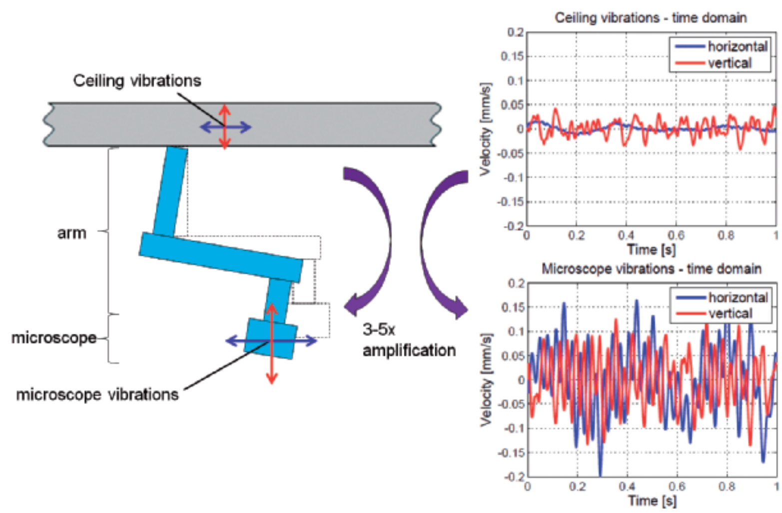

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- Wind
  After extensive measuring, it was found that microscope vibrations increased with increasing wind speeds.
- Air handling units
  The air handling units on the floor directly above the microscope were also disturbing the image quality.

The combination of these vibration sources resulted in vibration of the ceiling to which the surgery microscope was mounted. The measured vibrations at the ceiling are shown in Figure 2; results are displayed in velocity units. It is important to note that image quality is directly dependent on the displacement of the microscope, rather than the velocity. For the same velocity, displacement of a low-frequent vibration is higher than displacement of a high-frequent vibration. Therefore, the low-frequent vibrations have more effect on image quality.
The measurements showed significant vibrations in both horizontal and vertical directions. Horizontal vibrations were mostly seen at low frequencies, due to the building's resonance frequency at 2-4 Hz (horizontal movement of the building in Figure 1). Vertical vibrations were mostly seen at higher frequencies between 10 and 30 Hz, caused by the vibrations of air handling units, in combination with the resonance frequencies of the ceiling.

Not only the building vibrations, but also the vibrations of the microscope have been measured. It was found that the vibration amplitudes of the microscope were 3-5 times larger than those measured at the ceiling (Figure 3). To find the cause of this amplification effect, MECAL determined the natural vibration modes (mass and stiffness properties) of the microscope arm with modal analysis techniques (Figure 4). This measurement showed that the resonance frequencies of the microscope can be found in the

2 *Fourth-floor ceiling vibration measurement.*
3 *Vibration amplification by the microscope arm.*

frequency range 2-4 Hz and 10-30 Hz, coinciding with the resonance frequencies of the building. This explained the amplification of vibrations of the building in the microscope.

The resonance frequencies of any construction are determined by its mass and stiffness properties; the resonance frequencies increase with increasing stiffness and decrease with increasing mass. In case of the surgery microscope typically the joints, the pendulum-like shape and the dimensions of the microscope are optimised to enable easy manipulation and adjustment of its position during use. This limits the stiffness, resulting in low resonance frequencies. Furthermore, because of the shape of the microscope, the vibrations at the microscope tip are seen both in horizontal and vertical directions.

The measurements showed significant motion of the microscope tip, which was visible on the images produced by the microscope at high magnification. Based on this, the following two main requirement specifications were proposed:
S1) Dominant microscope vibrations between 2-30 Hz must be decreased by at least a factor of 10, in both horizontal and vertical direction.
S2) Microscope mobility and robustness may not be altered; the user should be able to use the microscope in the same way as they would the original microscope.

Concepts

Based on the requirements, a robust platform is needed that provides vibration isolation in six degrees of freedom, i.e. in horizontal and vertical displacements and all rotations. Various technologies were evaluated in order to determine the optimal design.

Passive vibration isolation

The first concept for vibration reduction that was evaluated is passive isolation, which means that no actuators, sensors or any active components are used. To minimise vibrations a heavy table mass m and a support spring with stiffness k are used, as in Figure 5.

The resonance frequency at which the table starts to reduce vibrations can be easily determined by Equation 1, where the isolation factor $U_{table} / U_{ceiling}$ is approximated by Equation 2:

$$f_{iso} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (1)$$

$$Isolation \approx \frac{f_{iso}^2}{f_{iso}^2 - f^2} \qquad (2)$$

In these equations, k and m denote the support stiffness and table mass, and f is the frequency in Hz. Note that damping is not taken into account to simplify the equation. From these equations, the following conclusions can be drawn:

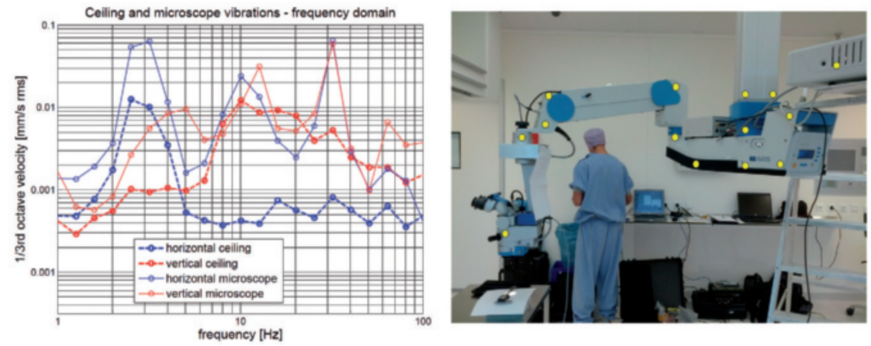
- In order to start isolating at low frequencies, a high-mass and low-stiffness design is necessary. However, these parameters are limited by the design:
  - The mass is limited due to available space and limitation in ceiling load.
  - The support stiffness is limited because of specification S2: when the support stiffness becomes too low, the table is sensitive to drift and 'feels' very unstable to the user.
- Equation 2 shows that isolating at least a factor of 10 is only possible at frequencies higher than three times the isolation frequency. Therefore, in practice, it is impossible to achieve 10x isolation of the microscope below 10 Hz with a passive system.

Typical passive vibration isolation systems start isolating at around 5 Hz. For this particular example, the system starts isolating at 7 Hz as is shown in the right side of Figure 5.

Overall, the passive vibration isolation solution is very effective to solve the higher-frequency problems, e.g. vibrations caused by air handling units. However, isolating the ceiling vibrations at frequencies of 2-4 Hz by a factor 10 is impossible with a passive vibration isolator alone.

Active vibration isolation

In active vibration isolation systems, sensors and actuators are used to measure and counter vibrations, often in combination with a passive isolation platform. The improvement with respect to the passive system is demonstrated in Figure 6.



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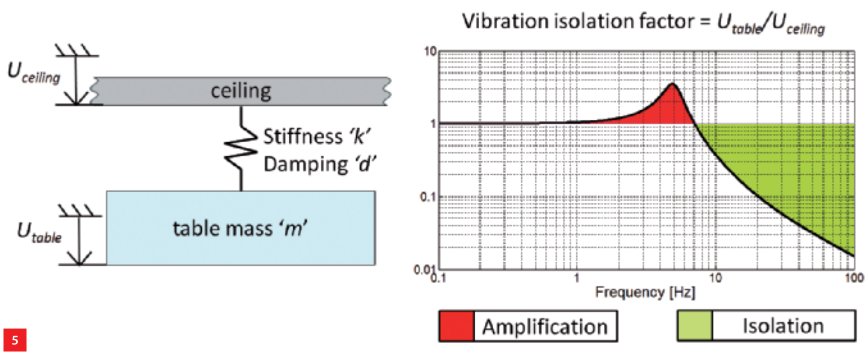

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The active system improves vibration isolation in the controller's bandwidth, in this case between 0.5 and 30 Hz. Also, the passive part of this system can be designed with higher support stiffness, resulting in better performance of the microscope with respect to specification S2. Three major challenges exist when designing active vibration isolation in all directions:

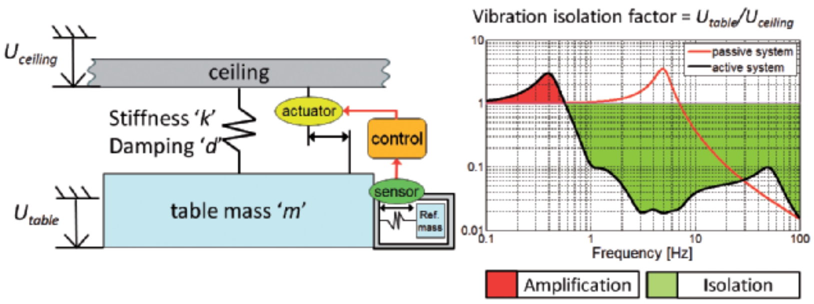
- structural dynamics,
- sensor and electronic noise,
- tilt-to-horizontal coupling.

For a more detailed description of design properties of active vibration isolation systems, see [1].

Structural dynamics

Structural dynamics concerns the natural frequencies and modeshapes of the entire system of ceiling, Hummingbird platform and microscope. Interaction exists between structural dynamics and the motion controller. This interaction can limit the controller's bandwidth, and therefore reduce the frequency range in which the vibration isolator is effective.
In this case, structural dynamics has been evaluated by use of a Finite Element Model (FEM). This model is used in a virtual prototype with which the structural dynamics of the system is simulated in combination with the effects of the motion controller. These simulations include performance and stability calculations that predict whether the design will function according to the specifications. Typical trade-

4 *Frequency domain velocity results (left) and modal analysis measurement (right, sensors indicated with yellow dots).*
5 *Passive vibration isolation.*



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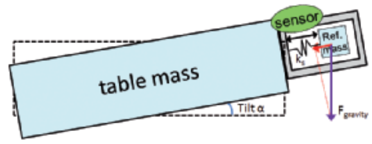

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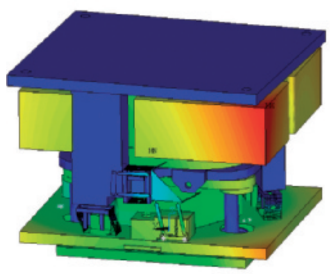

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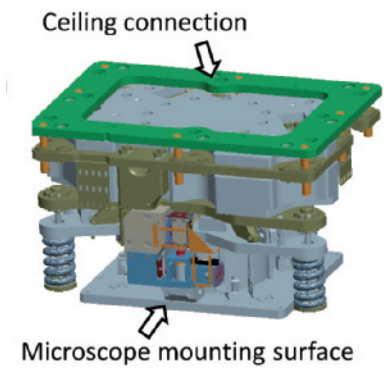

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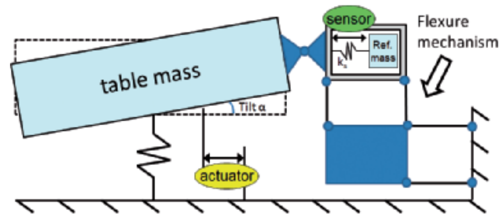

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offs are seen for resonance frequency specifications, between mass, stiffness, and design dimensions.

An example of an FEM result is shown in Figure 7. On the left a calculated modeshape of an earlier version of the design is shown, with the various colours depicting the motion amplitude (blue = small, red = maximum). On the right, the optimised final design of the Hummingbird platform in CAD is shown.

Sensor and electronic noise

At low frequencies the velocity measured with a sensor (geophone) decreases to very low levels. Therefore, the sensor signal becomes very small and eventually the noise produced by the sensor and other electronic components becomes dominant. A low-noise sensor design in combination with low-noise high-accuracy electronics is required to achieve high vibration isolation performance in the Hz and sub-Hz frequency ranges.

Tilt-to-horizontal coupling

Inertia sensors, such as geophones, are suitable to measure motion at low frequencies. These sensors consist of a reference mass, suspended with a low-stiffness spring, which can move with respect to its housing. The reference mass is intended to move only in the direction in which motion is measured with that sensor.
A disadvantage of inertia sensors is the tilt-to-horizontal coupling problem, which limits the stability of the

6 Active vibration isolation.
7 The optimised final design of the Hummingbird platform. (a) Example of a FEM-simulated modeshape. (b) Final geometry in CAD.
8 Tilt-to-horizontal-coupling problem.
9 Hummingbird technology: solution for tilt-to-horizontal coupling.

controller at low frequencies, see Figure 8. This problem only occurs in active vibration isolation systems where not only vertical but also horizontal vibrations must be isolated. The gravity has a force component due to the tilt angle α, which presses against the sensor stiffness k_s. This results in movement of the reference mass in the horizontal motion sensor. Therefore, tilt will be misinterpreted as horizontal motion, causing cancellation errors of the controller. This effect becomes dominant at frequencies below the sensor resonance frequency and therefore limits the vibration isolation factor at low frequencies.

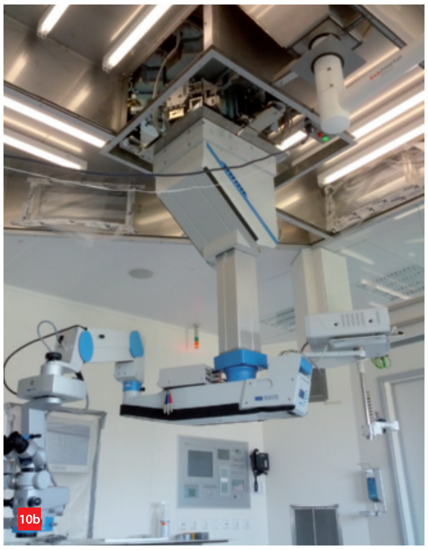
In cooperation with TNO, MECAL has successfully developed and patented a flexure mechanism to overcome this limitation, see Figure 9. The implementation of this mechanism in active vibration isolation is known as the Hummingbird technology, as described in [1].

The flexure mechanism prevents the horizontal sensor from tilting (Figure 9) and therefore eliminates the tilt-to-horizontal coupling problem. As a result, the Hummingbird platform provides isolation at much lower frequencies than other state-of-the-art active solutions and offers significantly better isolation performance in the 0.5-30 Hz range, which is critical for the microscope image quality.

Realisation

Figure 10a shows the Hummingbird active vibration isolation platform as realised for the surgery microscope at

10a



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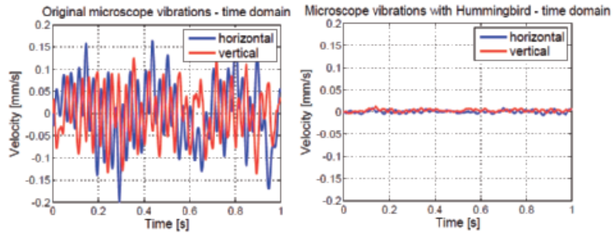

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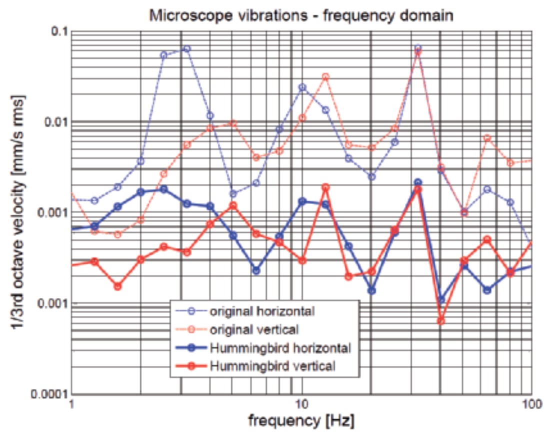

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azM. With its compact dimensions of 900 x 800 x 600 mm^3 the Hummingbird platform was designed to fit in the available space between microscope interface and ceiling. Figure 10b shows the microscope mounted to the Hummingbird platform in the operation room. The microscope itself, including its interfaces, has not been adapted and functions as if it were mounted directly to the ceiling.

Results

After installation of the Hummingbird platform, all visible microscope image vibrations were eliminated, even for the highest microscope magnification factors. The vibrations of the microscope have been measured and compared to the original situation, see Figure 11. In Figure 11a the vibrations of the microscope tip are shown before and after installation of the Hummingbird platform. In Figure 11b the vibration levels as a function of frequency are depicted.

The main specifications have been met:

S1) The improvement factor, highest peak to highest peak, ranges from 20 to 35 in both horizontal and vertical directions for the most dominant vibrations, exceeding the specification S1 of a factor of 10 improvement.

S2) Due to the stiff support spring design, the microscope arm can be treated in the same way by the users as the original microscope. Also, due to the robustness of the Hummingbird platform, the microscope can be used in several positions without compromising image quality. Therefore, specification S2 is also met.

Conclusion

Building vibrations can cause image quality loss in today's high-sensitive microscope applications. At the azM academic hospital, the low resonance frequencies of the building coincided with resonance frequencies of a microscope used for microsurgery. At high magnification factors of the microscope this resulted in unacceptable loss of image quality.

When disturbances at low frequencies are dominant, the conventional passive and active vibration isolation systems can no longer solve the problem. Based on Hummingbird technology, a robust six-degrees-of-freedom vibration isolation platform was implemented that counteracts vibrations at low frequencies better than any other state-of-the-art vibration isolation solution.
Both the horizontal and the vertical vibrations of the microscope are effectively isolated over the whole frequency range without deteriorating the microscope's user-friendly operation properties.

The Hummingbird platform is now used every day as a stable base for microsurgery operations to the full satisfaction of the surgeons at azM.

10 *The Hummingbird active vibration isolation platform in the operation room at azM.*
(a) Mounted to the ceiling.
(b) Microscope mounted on the platform.

11 *Vibration isolation performance of the Hummingbird platform.*
(a) Time domain.
(b) Frequency domain.

REFERENCES

[1] B. Bakker and J. van Seggelen, 2010, "The revolutionary Hummingbird technology", *Mikroniek* 50 (2), pp. 14-20.

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