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Key points
- Negative-stiffness isolators use mechanical components to keep vibrations from sensitive equipment.
- Negative-stiffness systems' 0.5-Hz resonant frequencies give them better low-frequency isolation efficiency than pneumatic systems.
- Equipment that detects features on the atomic scale benefits from the lower-noise environment negative-stiffness systems provide.

Resources
Minus K Technology, *minusk.com*
"Smoothing out bad vibes," Machine Design, Feb. 26, 1993, has a detailed discussion of the mechanics of negative-stiffness isolators.

Negative stiffness a big positive for VIBRATION ISOLATION

All-mechanical systems shield delicate electronics from low-frequency vibrations and require less space, investment, and maintenance.

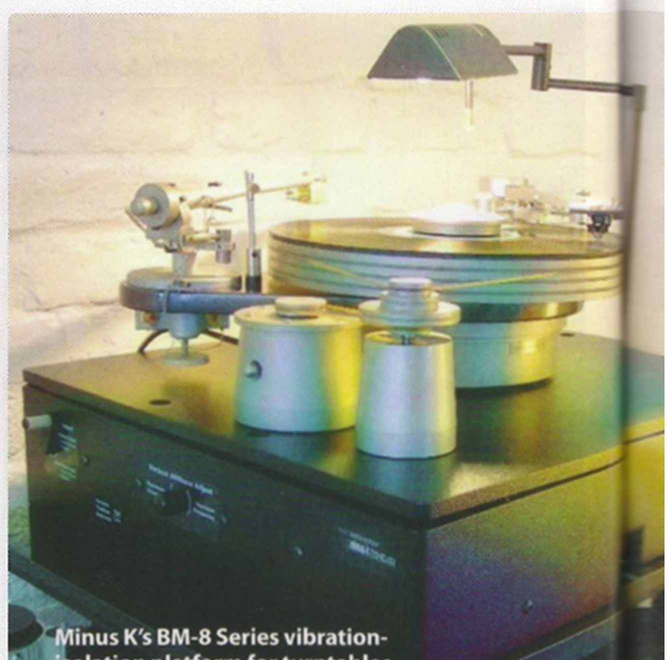
If you're trying to isolate sensitive equipment from vibrations, air tables and other pneumatic systems come to mind. The low-frequency vibration isolation and precise control needed to support state-of-the-art instruments for microelectronics fabrication, industrial laser and optical systems, biological research, and other areas may seem to call for expensive active vibration isolators, but negative-stiffness vibration isolators can provide the necessary protection at a reasonable cost.

Vibration basics

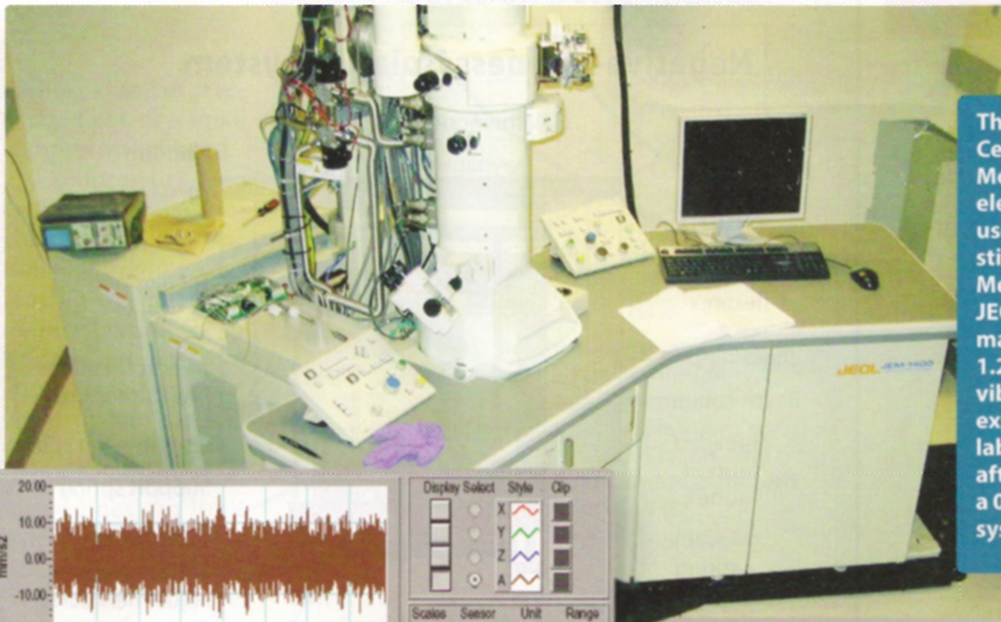
Vibration isolators keep incidental vibrations in the environment from damaging or otherwise disturbing equipment. These environmental vibrations come from many sources, according to Dr. David Platus, president and founder of **Minus K Technology,** Inglewood, Calif., and principal inventor of negative-stiffness vibration-isolation technology.

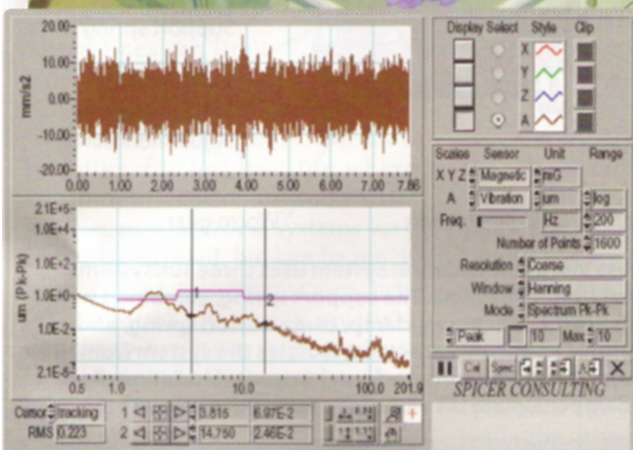
"One source of vibrations in a building is HVAC equipment mounted on the roof. People walking around in the building generate vibrations, too. In taller buildings, wind can cause movement, particularly horizontal oscillations. Vehicle traffic is another vibration source," Platus says.

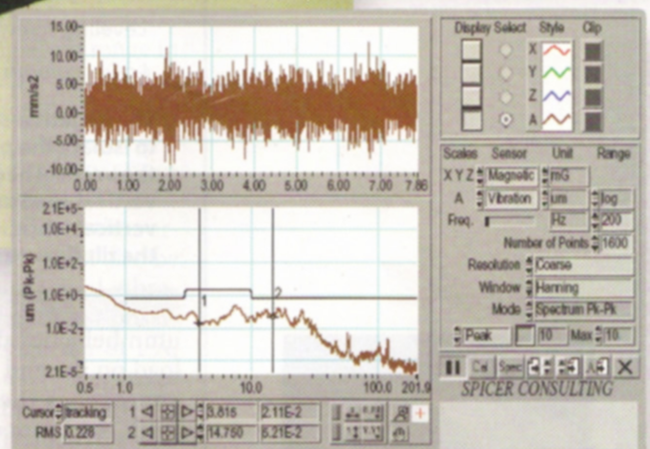
Environmental vibrations like these can have frequencies as low as 2 Hz. Pneumatic systems typically have a resonant frequency around 2.3 Hz, so they are not effective at isolating equipment from low-frequency vibrations of this nature. Negative-stiffness isolators, on the other hand, with a resonant frequency at 0.4 to 0.5 Hz, can screen out these lower-end fre-



Minus K's BM-8 Series vibration-isolation platform for turntables, CD transports, and other audio components provides 0.5-Hz isolation performance vertically and 1.5-Hz isolation horizontally.







The University of Texas Center for Learning and Memory's transmission electron microscope (TEM) uses a Minus K negative-stiffness isolation platform. Measurements courtesy JEOL U.S.A., the TEM manufacturer, show the 1.2 to 2.5-Hz horizontal vibrations the equipment experienced in its fifth-floor lab before (below left) and after (below) isolation with a 0.4-Hz negative-stiffness system.

quencies. Vibrations under 1 Hz are rare; when they do occur they carry little energy that can affect the payload.

While users need to consider the range of frequencies in the environment and which frequencies will most severely effect the equipment being isolated, the vibration-isolation efficiency is another consideration.

Isolation efficiency is the percentage of vibration energy that gets past an isolation system into the equipment and is inversely related to the transmissibility. Negative stiffness systems' low resonant frequency means they exhibit lower transmissibility at lower frequencies than pneumatic systems can. They also transmit less vibration energy over the entire range of building vibration frequencies of concern. A system with a 0.5-Hz natural frequency has a 93% isolation efficiency at 2 Hz. The efficiency grows to 99% at 5 Hz and 99.7% at 10 Hz.

The positives of negative stiffness

So how do negative-stiffness isolators produce their high isolation efficiencies? And what exactly is negative stiffness?

Negative-stiffness isolators use one system to isolate payloads from vertical motions and a different one to protect equipment from horizontal motions. Both systems use a negative-stiffness mechanism to keep overall stiffness and, therefore, resonant frequency low. The mechanisms differ slightly for each direction of movement.

In the vertical direction, a stiff spring supports the payload weight. Stiff systems have higher resonant frequencies and tend to transmit more vibrations to the load, so a negative-stiffness mechanism perpendicular to the spring's axis lowers overall stiffness.

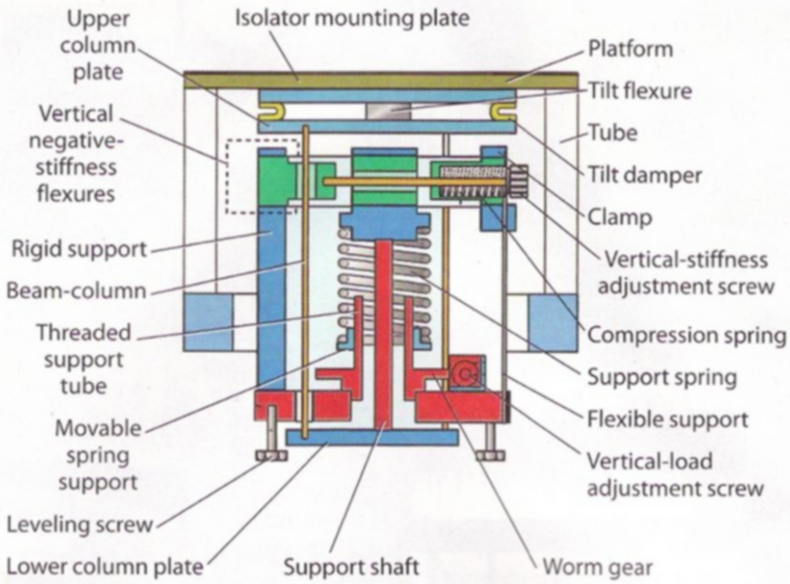
Horizontal flexures attach to the top of the spring. The flexures are preloaded in compression so that the horizontal position represents an unstable equilibrium when the preload compresses the spring. This unstable equilibrium has the same effect as a negative stiffness in the vertical direction.

The spring's positive stiffness, defined by its spring constant, K_s, means that it compresses a given amount under a given weight load and resists further compression. The flexures, on the other hand, provide less resistance to deflection the more their position departs from horizontal. This contrary behavior can be represented by a negative stiffness, K_n.

Engineers setting up the system adjust the horizontal compression preload and spring position so K_n approaches K_s. The result is a low overall stiffness, which translates to low-resonant frequency.

In the horizontal direction, vertically oriented beam-columns provide vibration isolation. Classic beam-col-

Negative-stiffness isolation system



The negative-stiffness vibration-isolation system uses three subsystems to isolate the payload from vibrations. The support spring, combined with the vertical negative-stiffness flexures, clamp, compression spring, and vertical-load and stiffness-adjustment screws, isolates the system from vertical vibrations. The beam-columns perform horizontal isolation. And the tilt flexure and damper isolate tilt vibrations from the payload.

umn behavior dictates that as the load on the end of a beam-column approaches the critical buckling load, the beam column's horizontal stiffness approaches zero with a corresponding drop in resonant frequency.

Beam columns can be modeled by two cantilevered beams meeting at their free ends. Each cantilevered beam behaves as a horizontal spring comparable with the spring in the vertical-vibration isolator. The beam-column effect provides the negative-stiffness mechanism.

For horizontal isolation, the payload itself is the preload that gets the overall system's stiffness to approach zero. Systems are sized for a range of payload weights, with the best isolation performance toward the top of the weight range.

Mechanical benefits

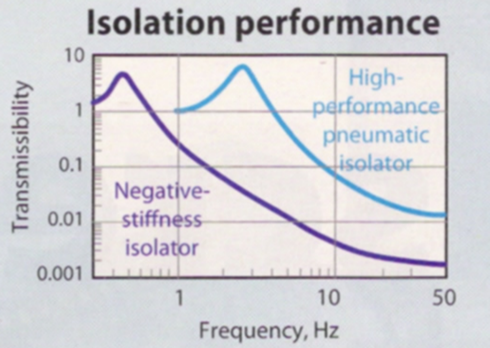
The horizontal and vertical-isolation systems combine for an overall vibration-isolation product that is purely mechanical in nature. This simplicity gives negative-stiffness systems several advantages over pneumatic systems, in addition to the ability to isolate at frequencies pneumatic systems find problematic.

Negative-stiffness isolators can be designed for use in adverse environments such as vacuum and high and low temperatures, due to their all-metal construction. By contrast, pneumatic systems run into problems when users need vibration isolation in such environments.

"Pneumatic isolators can be used in vacuum chambers, but they require very special seals and there is a risk they can leak," says Platus. "High-performance pneumatic isolators have sensors, valves, and pumps that keep them level. If the payload mass is redistributing, the system wants to add or release air to keep the table level."

In addition, pneumatic systems require compressed air that can be tricky to feed into the sealed vacuum chamber. The need for a compressed-air supply means users must have a dedicated compressed-air line, a tank of pressurized gas, or a small compressor on hand.

Compressors generate their own mechanical and acoustic noise, sometimes defeating the purpose of the vibration-isolation system. Tanks of compressed gas can be costly and dangerous if not mounted properly. Finally, dedicated lines can limit where in a room users can place isolation systems.



Negative-stiffness isolators have resonant frequencies at 0.4 to 0.5 Hz, compared to 2.3 Hz for pneumatic systems. They transmit less energy from low-frequency vibrations to the payload than do pneumatic systems, and maintain better isolation performance through building frequencies to about 100 Hz.

Pneumatic systems can also be bulky, further limiting where equipment can be housed in the lab. Negative-stiffness systems vary in size by payload, but can be much more compact. In many cases, better isolation efficiency means a benchtop negative-stiffness unit is sufficient to isolate a piece of equipment from environmental vibrations.

Simplicity can mean less maintenance and longer life, too. Negative-stiffness isolators are designed for repeated elastic deformation. The components do not deform plastically or fatigue over time.

Cost-wise, negative-stiffness isolators are comparably priced to air isolators. For many applications, they can represent a lower-cost way to isolate sensitive equipment.

"Active vibration-isolation systems cost two to three times what negative-stiffness isolators do," says Platus. "Negative-stiffness units' cost can be comparable or even less than passive pneumatic units, especially if users can replace big, freestanding air tables with better-performing negative-stiffness benchtop units."

Applying isolation

Researchers and engineers have found negative-stiffness vibration isolation to be useful in sensitive analyses like atomic force microscopy (AFM). Noise in AFM signals can be cut down by a factor of two to three with negative-stiffness units when compared with top-performance air tables. Reducing noise levels in the sub-Angstrom range in particular brings clearer images that let researchers see features the noise otherwise obscures.

Scanning-probe microscopes (SPMs) require unparalleled vibration isolation, especially in the vertical axis, although they can also be quite sensitive to horizontal vibrations. To achieve the lowest possible noise floor, on the order of 1 Å, isolation is always used. Negative-stiffness isolators let users tailor the system's resonant frequencies vertically and horizontally without increasing complexity or facilities requirements.

Laser and optical systems are also extremely susceptible to vibrations from the environment. Traditionally, large air tables have been preferred for optical systems, but negative-stiffness isolators are becoming a more common choice, especially since they can provide 10 to 100× better isolation efficiency, depending on vibration frequency.

Laser-based interferometers can resolve nanometer scale motions and features. The sophisticated modern ellipsometry techniques that allow this high performance rely on low noise for fringe-movement detection. Properly isolating an interferometer improves resolution. Optical profilers have similar sensitivity to vibrations due to their complexity. Long optical paths can lead to angular magnification of vibrations. **MD**