Engineeringtalk

Negative-stiffness vibration isolators explained

A Minus K Technology product story
Edited by the Engineeringtalk editorial team **January 25, 2008**

Although air tables have been around for the better part of a half-century, their usefulness as an efficient method for vibration isolation is now being seriously challenged, says Jim McMahon.

For almost 40 years pneumatic vibration isolators have been the mainstay for stabilising industry and academia's most critical micro-engineering instrumentation. But, just as technology has been steadily migrating from micro to nano, so has the need for more precise vibration isolation in microelectronics fabrication, industrial laser/optical systems and biological research.

These so called "passive system" air tables are now being seriously challenged by the newer negative-stiffness vibration isolators. Negative-stiffness isolation is rapidly gaining popularity in industrial and laboratory environments, and to no small degree because of its ability to effectively isolate vibration in diverse and challenging environments. An isolator is used to solve a problem, and how bad the problem is determines the solution you need.

Since the 1960s air tables have been used for isolation. Basically cans of air, they are still the most popular isolators used. But, air tables with resonant frequencies at 2 to 2.5Hz can typically only handle vibrations down to about 8 to 10Hz - not quite low enough for optimum performance with modern nanoscale equipment. Also, greater isolation efficiencies are needed in the frequency ranges air isolators can handle. For purposes of clarity in scanning probe microscopes and interferometers, air tables are an inefficient isolation solution. The air systems have been adequate up until a few years ago when better isolation was required.

Because of its very high isolation efficiencies, negative-stiffness vibration isolation systems enable vibration-sensitive instruments such as scanning probe microscopes, micro-hardness testers, profilers and scanning electron microscopes to operate in harsh conditions and severe vibration environments that would not be practical with top-performance air tables and other pneumatic isolation systems.

Negative-stiffness isolators employ a unique - and completely mechanical - concept in low-frequency vibration isolation. Vertical-motion isolation is provided by a stiff spring that supports a weight load, combined with a negative-stiffness mechanism. The net vertical stiffness is made very low without affecting the static load-supporting capability of the spring.

Beam columns connected in series with the vertical-motion isolator provide horizontal-motion isolation. The horizontal stiffness of the beam-columns is reduced by the "beam-column" effect. (A beam column behaves as a spring combined with a negative-stiffness mechanism).
The result is a compact passive isolator capable of very low vertical and horizontal natural frequencies and very high internal structural frequencies. The isolators (adjusted to 0.5Hz) achieve 93% isolation efficiency at 2Hz; 99% at 5Hz; and 99.7% at 10Hz.

There are ten key points that demonstrate the benefits of negative-stiffness isolators compared with air isolation systems.

First. an air table will amplify vibrations in a typical range of 2 to 7Hz; this is because of the natural frequencies where air tables resonate. All isolators will amplify at their resonant frequency, and then they will start isolating. So, with an air table, any vibration in that range could not only fail to be mitigated: it could be amplified. The low cycle perturbations would just come straight through to the instrument. Negative-stiffness isolators resonate at 0.5Hz. At this frequency there is almost no energy present. It would be very unusual to find a significant vibration at 0.5Hz.

Secondly, negative-stiffness vibration isolation can reduce vibration noise levels in atomic force microscopes, for example, by a factor of two to three when compared with top-performance air tables. This is particularly significant for noise levels in the sub-Angstrom range. This results in clearer images and features not discernable with pneumatic isolation systems.

Thirdly, as nanoscale equipment use becomes more prevalent, lab sites are being set up in much more severe vibration-prone environments, such as upper floors of buildings and clean rooms. Such severe vibration locations are too extreme for pneumatic isolators to effectively do their job. But negative-stiffness isolators perform well in such environments, producing much better images and data than can be obtained with even the best high-performance air tables.

Fourthly, air tables are not particularly compatible when it comes to operating in vacuums, extreme high and low temperatures, and radiation. Yet these harsh operating environments are often necessary when conducting research and testing, such as with cryogenic chambers in semiconductor research. All-metal negative-stiffness systems can be configured to be compatible with high vacuums and other adverse environments, such as extreme high and low temperatures, and radiation.
With vacuums, for example, negative-stiffness isolators can be used right inside the vacuum chambers. This offers other advantages such as much lower payload weights, more compact systems, and eliminates problems associated with vacuum chamber feedthrough.

Fifthly, air tables require a constant supply of compressed air. This requires either a dedicated compressed air line to be plumbed in to your lab, a tank of pressurised gas or a small compressor. Even if you are lucky enough to have a dedicated compressed air line your table's location is still limited by the length of air line you have. Large tanks of compressed gas have to be mounted very securely to minimise their danger. Changing the tanks can be quite difficult and inconvenient as well. Compressors are sources of both mechanical and acoustic noise and are very poor choices from a vibration standpoint. If you can get your nano-environment mechanically isolated without having to deal with compressed air to run your vibration isolator, then you will be better off. The nice thing about Negative-Stiffness isolators is they do not require compressed air. They operate purely in a mechanical mode. One less thing you have to worry about when you are setting up your lab and working in it.

Sixthly, air tables are big, bulky structures, and they take up a lot of lab space. The high-performance air tables are even bigger. This can become a limiting factor when laying out the equipment in your lab. Negative-stiffness isolators are available in high-performance benchtop configurations, considerably more compact than air tables and easy to move around. They are also available as workstations, tables and floor platforms where these configurations are required.

Seventhly, low-frequency passive vibration isolators are somewhat sensitive to small changes in weight loads, as well as to large displacements. Pneumatic systems use levelling valves to mitigate the problem. Negative-stiffness isolators provide very simple manual adjustment to accommodate variations in weight loads. For applications where manual load adjustment is not practical they provide an auto-adjust system that maintains the isolator in a precise vertical equilibrium position.

Eighthly, scanning probe microscopes (SPMs) have vibration isolation requirements that are unparalleled in the metrology world. The vertical axis is the most sensitive for most SPMs. They can also be quite sensitive to vibrations in the horizontal axes. In order to achieve the lowest possible noise floor, on the order of an Angstrom, isolation is always used. Benchtop air systems provide limited isolation vertically and very little isolation horizontally. Negative-stiffness isolators provide increased isolation performance for SPMs over air tables, while offering better ease of use and no facility requirements. Negative-stiffness isolators have the flexibility of custom tailoring resonant frequencies vertically and horizontally.

Ninthly, laser and optical systems, whether used in an academic lab or in an industrial environment, are very susceptible to vibrations from the environment. These instruments almost always need vibration isolation. Traditionally, large air tables have been the isolators preferred for optical systems, but Negative-Stiffness isolators are becoming a popular choice. Negative-stiffness isolators provide 10 to 100x the performance of air tables, depending on the vibration frequency. Laser based interferometers are extremely sensitive devices that are capable of resolving nanometre scale motions and features. They often have very long mechanical paths which makes them even more sensitive to vibrations.

The sophisticated modern ellipsometry techniques that allow this high performance rely on low noise to be able to detect fringe movement. Properly isolating an interferometer will allow it to provide the highest possible resolution. Optical profilers have similar sensitivity to vibrations. Optical component systems are often quite complex. The long optical paths can lead to angular magnification of vibrations. Optical air tables can make the problems worse since they have a resonant frequency that often matches that of floor vibrations. Negative-Stiffness 0.5Hz isolators provide isolation in these environments when air tables simply cannot.

Finally, because negative-stiffness isolators utilise simple elastic structures and viscoelastic materials that deform, their isolation performance does not degrade with micromotions typical of laboratory floors and fabrication rooms, as do conventional pneumatic isolators. Cost-wise, negative-stiffness isolators are comparably priced to air isolators or lower priced for many applications. The need for vibration isolation will continue to increase in importance as the precision of research and test applications embraces smaller and smaller magnitudes of scale.

As industrial researchers and universities continue to broaden their nanotech work, necessitating more sensitive equipment and expanded lab facilities, vibration-handicapped environments will become more prevalent, and a better vibration isolation solution will be required than what has been available for the past almost half-century with air tables. It appears negative-stiffness vibration isolation will fill that void.