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NEGATIVE-STIFFNESS-MECHANISM VIBRATION ISOLATION SYSTEMS

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ABSTRACT

Negative-Stiffness-Mechanism (NSM) vibration isolation systems offer a unique passive approach for achieving low vibration environments and isolation against sub-Hertz vibrations. "Snap-through" or "over-center" NSM devices are used to reduce the stiffness of elastic suspensions and create compact six-degree-of-freedom systems with low natural frequencies.

Practical systems with vertical and horizontal natural frequencies as low as 0.2 to 0.5 Hz provide isolation efficiencies one to two orders of magnitude better than top-performance air tables and pneumatic isolation systems. Electro-mechanical auto-adjust mechanisms compensate for varying weight loads and provide automatic leveling in multiple-isolator systems, similar to the function of leveling valves in pneumatic systems. All-metal systems can be configured which are compatible with high vacuums and other adverse environments such as high temperatures.

These isolation systems enable vibration-sensitive instruments such as scanning probe microscopes, micro-hardness testers and scanning electron microscopes to operate in severe vibration environments sometimes encountered, for example, on upper floors of buildings and in clean rooms. Such operation would not be practical with pneumatic isolation systems. Similarly, they enable vibration-sensitive instruments to produce better images and data than those achievable with pneumatic isolators.

The theory of operation of NSM vibration isolation systems is summarized, some typical systems and applications are described, and data on measured performance is presented.

KEYWORD LIST

Vibration / Isolation / Isolator / Platform / Suspension / Negative-Stiffness / Low-Frequency / Sub-Hertz / Microscopes / Micro-hardness.

THEORY OF OPERATION

The theory of NSM isolation systems is explained in References 1 and 2. It is summarize briefly for convenience.

Vertical-Motion Isolation

A vertical-motion isolator is shown in Figure 1. It uses a conventional spring connected to an NSM consisting of two bars hinged at the center, supported at their outer ends on pivots, and loaded in compression by forces P. The spring is compressed by weight W to the operating position of the isolator, as shown in Figure 1. The stiffness of the isolator is $K=K_S-K_N$ where K_S is the spring stiffness and K_N is the magnitude of a negative stiffness which is a function of the length of the bars and the load P. The isolator stiffness can be made to approach zero while the spring supports the weight W.

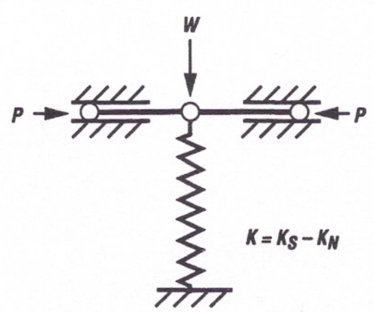

Figure 1 Vertical-Motion Isolator

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Horizontal-Motion Isolation

A horizontal-motion isolator consisting of two beam-columns is illustrated in Figure. 2. Each beam-column behaves like two fixed-free beam columns loaded axially by a weight load W. Without the weight load the beam-columns have horizontal stiffness K_S. With the weight load the lateral bending stiffness is reduced by the "beam-column" effect. This behavior is equivalent to a horizontal spring combined with an NSM so that the horizontal stiffness is $K=K_S-K_N$, and K_N is the magnitude of the beam-column effect. Horizontal stiffness can be made to approach zero by loading the beam-columns to approach their critical buckling load.

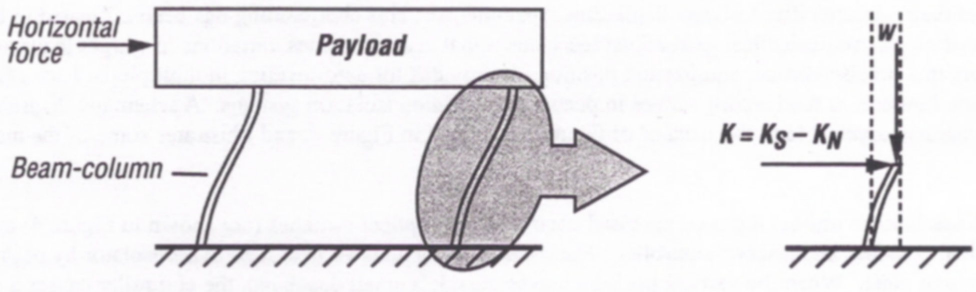

Figure 2 Horizontal-Motion Isolator

Six-Degree-of-Freedom (Six-DOF) Isolation

A six-DOF NSM isolator typically uses three isolators stacked in series: a tilt-motion isolator on top of a horizontal-motion isolator on top of a vertical-motion isolator. Figure 3 shows a schematic of a vibration isolation system consisting of a weighted platform supported by a single six-DOF isolator incorporating the isolators of Figures 1 and 2. Flexures are used in place of the hinged bars shown in Figure 1. A tilt flexure serves as the tilt-motion isolator. A vertical-stiffness adjustment screw is used to adjust the compression force on the negative-stiffness flexures thereby changing the vertical stiffness. A vertical load adjustment screw is used to adjust for varying weight loads by raising or lowering the base of the support spring to keep the flexures in their straight, unbent operating position.

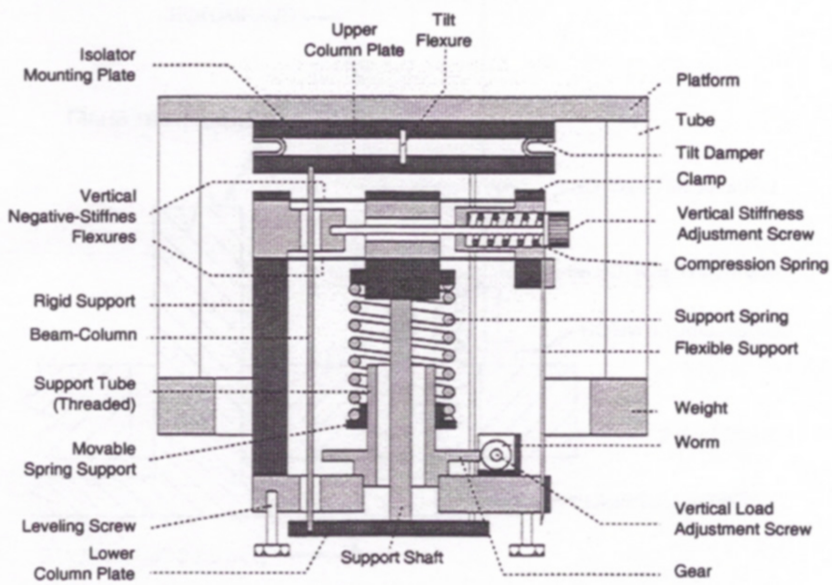

Figure 3 Schematic of Six-DOF Single-Isolator System

Damping

Structural damping inherent in NSM isolators limits the resonant responses at the natural frequencies. This damping is magnified by the use of NSMs, as explained in References 1 and 2. The damping magnification can be as high as 100 or greater, limiting the transmissibilities at the natural frequencies to values below 10. Additional damping is sometimes provided by the use of elastomeric damping elements, limiting the transmissibilities at the natural frequencies to values as low as 2 or 3.

Vertical Auto-Adjustment

One of the shortcomings of low-frequency passive vibration isolation systems has been their sensitivity to small changes in weight loads and their susceptibility to large displacement excursions. This shortcoming has been mitigated in NSM systems by the use of an electromechanical auto-adjust mechanism that accommodates variations in weight loads and maintains the isolators in a precise vertical equilibrium position. It provides for auto-leveling in multiple-isolator systems and provides the same function as the leveling valves in pneumatic vibration isolation systems. A schematic diagram of an auto-adjust mechanism applicable to the isolator of Figure 3 is shown in Figure 4, and illustrates some of the mechanism features.

The auto-adjust mechanism utilizes a pre-compressed control spring, optical switches (not shown in Figure 4) that sense changes in vertical position, and a servo-controller. The control spring adds vertical load to the isolator by pushing down on the lower column plate. When the vertical position moves outside a small deadband, the controller causes a gearmotor to drive a screw that changes the load on the spring and restores the isolator to its position within the deadband. A typical load range for the controller is +/- 2 to 3 Kg to accommodate different specimen weights in scanning probe microscopes (SPMs) and micro-hardness testers (MHTs), for example. A manual load-adjustment screw, such as that illustrated in the isolator of Figure 3, is used to bring the isolator into the range of the auto-adjust mechanism. A mid-point switch indicates when the controller is at the middle of its adjustment range and limit switches indicate when the controller has reached its adjustment limits.

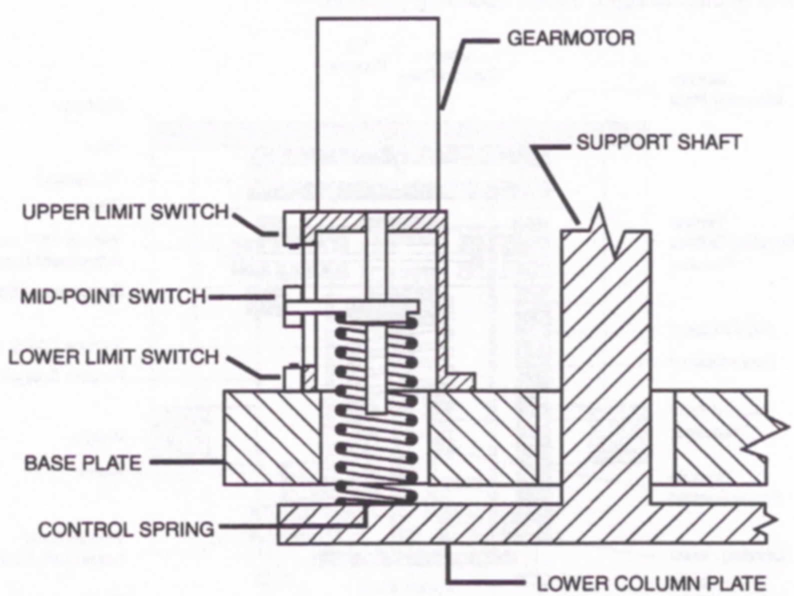

Figure 4 Vertical Auto-Adjust Mechanism

TYPICAL APPLICATIONS

Because of their very high isolation efficiencies, NSM vibration isolation systems enable vibration-sensitive instruments such as SPMs, MHTs and scanning electron microscopes (SEMs) to operate in severe vibration environments that would not be practical with top-performance air tables or other pneumatic isolation systems.

Figure 5 shows a Nano-K™* "Biscuit" NSM bench top vibration isolation platform supporting a Digital Instruments Dimension™ 3000 AFM. The platform is approximately 600 mm square and 200 mm high. Platforms of this type are capable of supporting payloads up to 160 Kg or more. Figure 6 shows the Digital Instruments IS3K Hood used with the Dimension™ 3100 AFM, which includes an acoustic shield and a custom Nano-K™ "Biscuit" NSM isolator. This hood allows the Dimension™ 3100 AFM to produce measurements at the nanometer (lateral) and sub-Angstrom (vertical) scales in noisy acoustic and vibration environments.

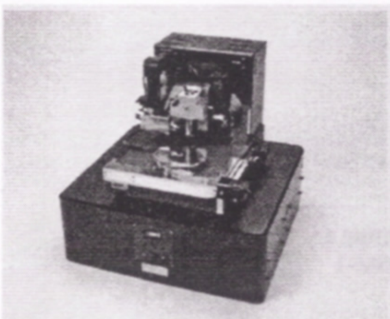

Figure 5 Nano-K™ "Biscuit" NSM Bench Top Vibration Isolation Platform with Digital Instruments Dimension™ 3000 AFM (courtesy of Digital Instruments, Veeco Metrology Group)

Figure 6
Digital Instruments IS3K Hood Incorporating custom Nano-K™ 150BA-1 "Biscuit" NSM Isolator (courtesy of Digital Instruments, Veeco Metrology Group)

*Nano-K is the trademark for Minus K Technology vibration Isolation Products.

An NSM vibration isolation floor platform for a SEM is shown in Figure 7. The platform uses three Nano-K™ 1000SM-1 isolators of the type shown schematically in Figure 3, each with a payload capacity of about 450 Kg. Figure 8 shows a workstation for an Elionix ENT-1100 Micro-Hardness Tester using a custom Nano-K™ 100SP-1 NSM single-isolator platform of the type shown schematically in Figure 3.

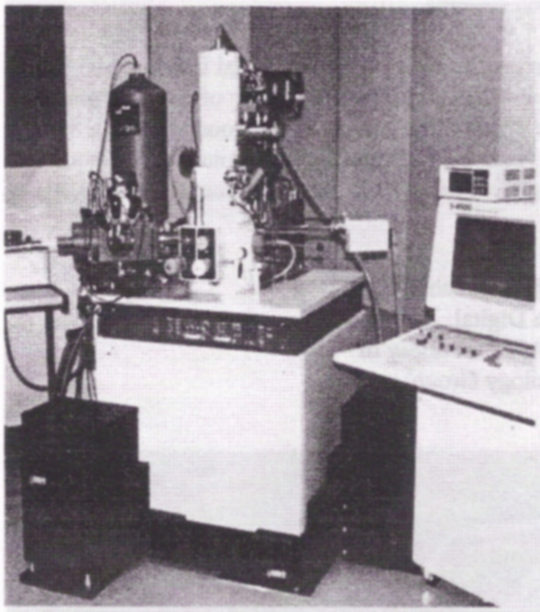

Figure 7 Floor Platform Supporting a SEM on Three Nano-K™ 1000SM-1 NSM Isolators

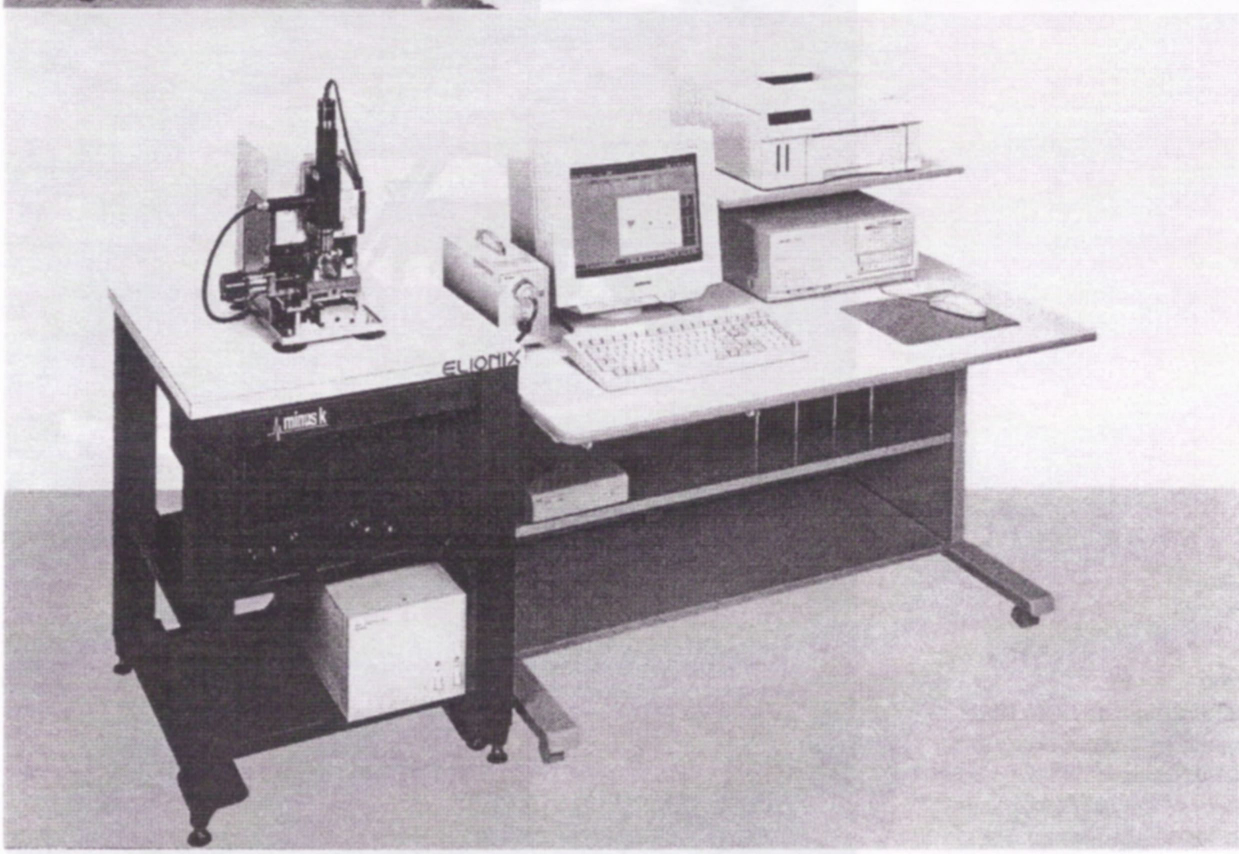

Figure 8 Elionix ENT-1100 Micro-Hardness Tester Workstation Using a Custom Nano-K™ 100SP-1 NSM Vibration Isolation Platform (Courtesy of Elionix Corporation, Japan)

All-metal NSM vibration isolation systems can be configured which are compatible with high vacuums and other adverse environments such as high temperatures. Small NSM platforms similar to that shown schematically in Figure 3, and measuring about 100 mm high and 150 mm in diameter, have been used to support scanning tunneling microscopes in ultra-high vacuums. These platforms have demonstrated vertical and horizontal natural frequencies as low as 0.5 Hz.

PERFORMANCE

Transmissibility Data

The behavior of NSM vibration isolation systems approximates that of six-DOF linear spring systems up to about 10 to 20 Hz. That is, isolation starts at a frequency of 1.4 times the natural frequency and rolls off at about 12 dB per octave with increasing frequency of the input vibrations. Above 10 to 20 Hz the transmissibility tends toward a constant "floor" value until internal structural resonances are reached. For 0.5-Hz systems this "floor" value is approximately -55 to -60 dB. The internal structural resonances in practical systems can be kept above 70 to 80 Hz or higher, while the system natural frequencies can be kept low. The natural frequencies of NSM isolation systems of the type shown in Figures 5 to 8 can be adjusted, typically, to 0.5 Hz or lower, vertically and horizontally. Some of them can be adjusted to frequencies as low as 0.2 to 0.3 Hz.

Figure 9 shows transmissibility data for a Nano-K™ 100SP-1 single-isolator NSM platform of the type shown schematically in Figure 3, with a natural frequency of approximately 0.5 Hz. It indicates transmissibilities of approximately -20 dB at 2 Hz, -40 dB at 5 Hz and -50 dB at 10 Hz.

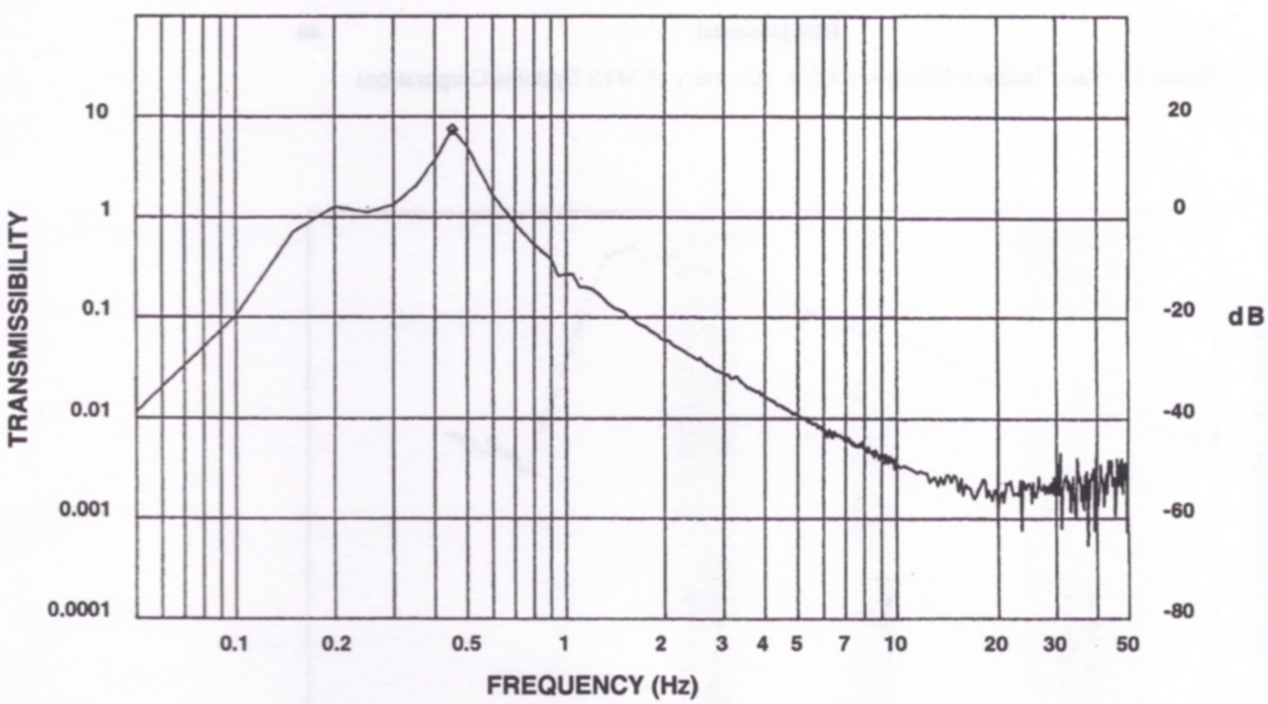

Figure 9 Transmissibility Data for a Nano-K™ 100SP-1 NSM Vibration Isolation Platform

Comparison of MHT Data Using NSM and Pneumatic Vibration Isolation Systems

Vibration response of a Nano Indenter XP manufactured by MTS Systems Corporation was compared on an NSM bench top vibration isolation platform and on a on a high-performance air table for severe vibrations produced by impacting the floor. The indenter was set up in a way to maximize its sensitivity to external vibrations. The data are shown in Figures 10 and 11 in terms of displacement voltage vs time.

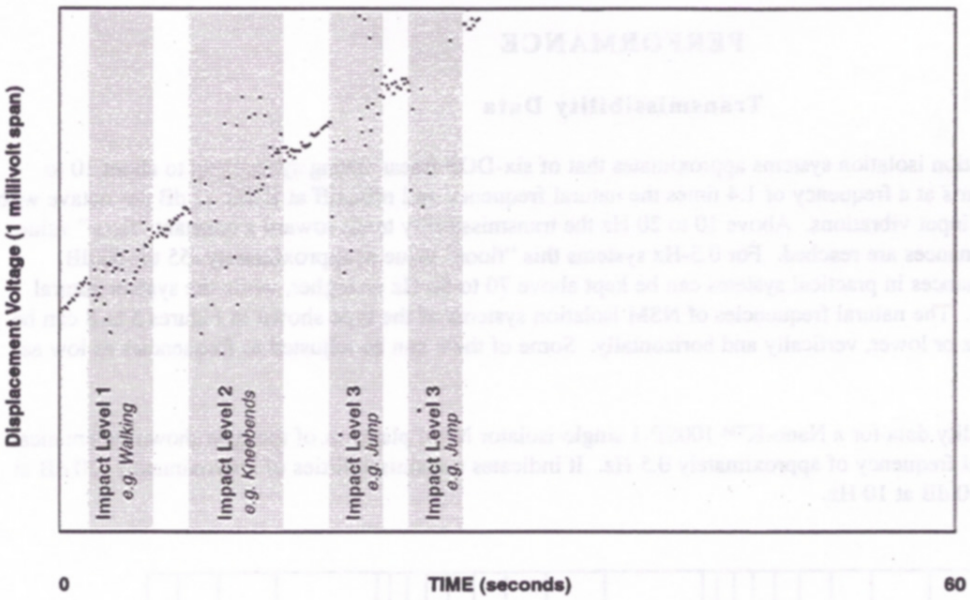

Figure 10 Nano Indenter XP on Air Table (Courtesy of MTS Systems Corporation)

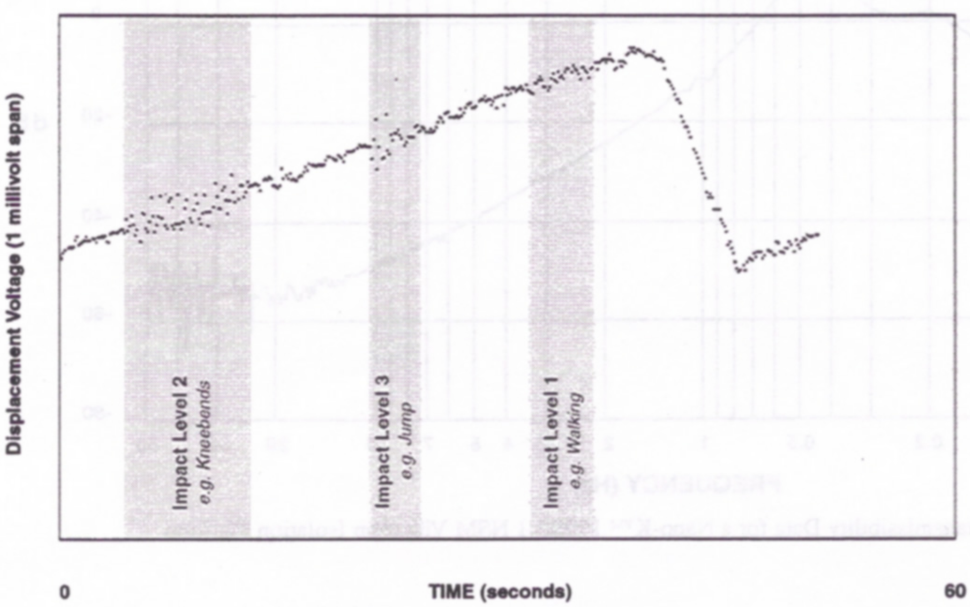

Figure 11 Nano Indenter XP on Nano-K™ 150BA-1 "Biscuit" Bench Top Platform
(Courtesy of MTS Systems orporation)

Micro-hardness data for Silicon taken on an Elionix ENT-1040 Ultra Micro-Hardness Tester supported on an air platform and on an NSM platform is shown in Figures 12 and 13.

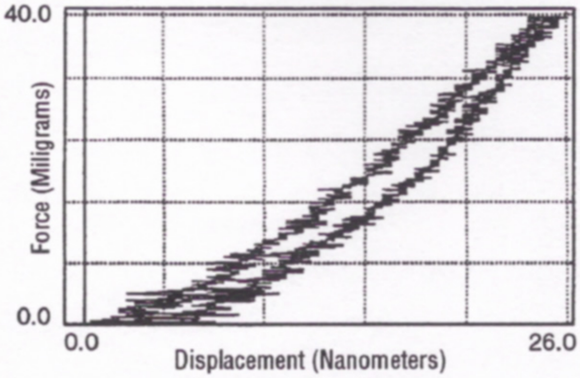

Figure 12 Micro-Hardness Data for Elionix ENT-1040 on Air Platform (Courtesy of Elionix Corporation.)

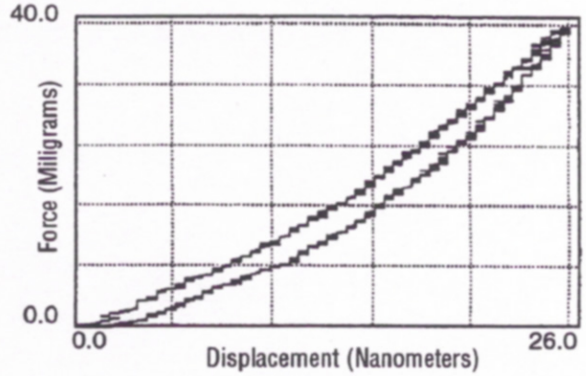

Figure 13 Micro-Hardness Data for Elionix ENT-1040 on Custom Nano-K™ 100SP-1 NSM Vibration Isolation Platform (Courtesy of Elionix Corporation.)

Comparison of AFM Data using NSM and Pneumatic Isolation Systems

Based on field test data, NSM vibration isolation systems such as those shown in Figures 5 and 6 typically reduce the vibration noise levels in AFMs by a factor of 2 to 3 or more when compared with top-performance air tables. This is particularly significant for noise levels in the sub-Angstrom range. The use of NSM vibration isolation systems result in clearer images and features not discernable with pneumatic isolation systems. They also enable AFMs to be used in severe environments that would not be practical with pneumatic isolators.

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2. Platus, D. L., "Negative-Stiffness-Mechanism Vibration Isolation Systems, SPIE Vol. 1619 Vibration Control in Microelectronics, Optics, and Metrology (1991) pp. 44-54.