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PHOTONICS SPECTRA

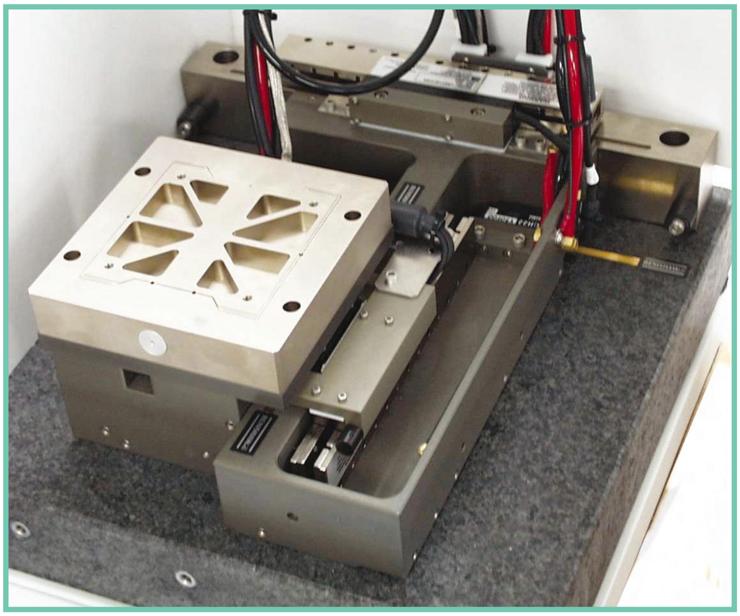
Eliminating Vibration in the Nano-World

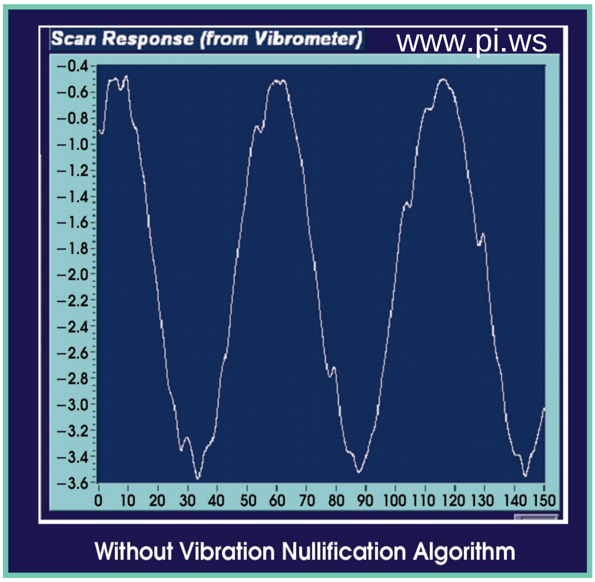
As in the macro-world, solutions to vibration problems range from simply increasing dwell time to allow settling, to using an algorithm in the controller to nullify resonance.

by Scott Jordan (scottj@polytecpi.com)

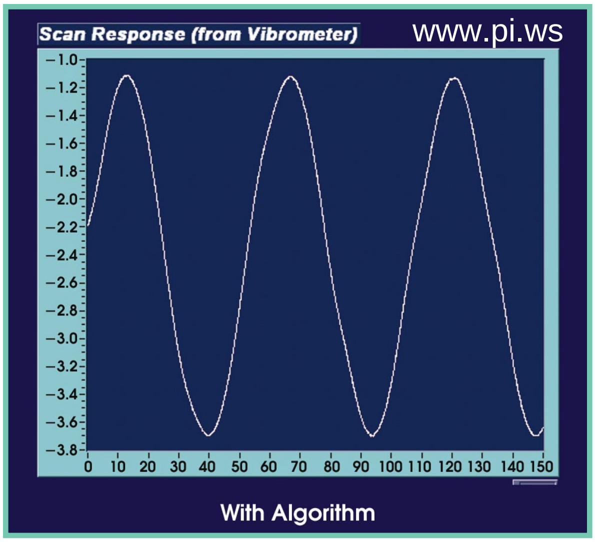
Until recently, photonics engineers, among others, had been powerless against settling-time bottlenecks in industrial processes that require submicron-scale precision. Their only effective ways to address fixturing and structural resonance excited by process motion had been either to slow down processes by using less aggressive motion profiles or to insert dwell times to allow mechanical damping to settle things down by converting any mechanical resonance into heat.

However, as process tolerances get tighter — especially with nanoscale applications such as those involving microelectromechanical





Without Vibration Nullification Algorithm



With Algorithm

Figure 1. *In the fiber Bragg grating manufacturing process, vibration of tooling components in response to rapid actuation of high-throughput nanopositioners can reduce process efficiency, as indicated by quasi-sinusoidal phase-mask dither waveforms, right. A resonance nullification strategy smooths the waveform significantly. Courtesy of Dover Instruments.*

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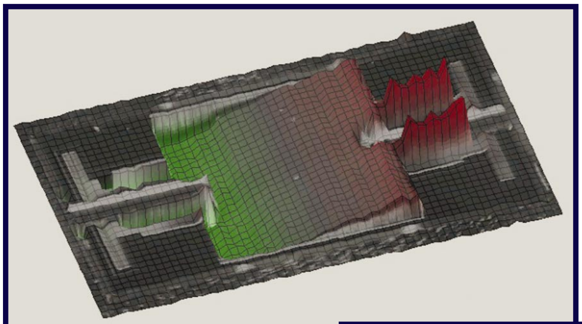
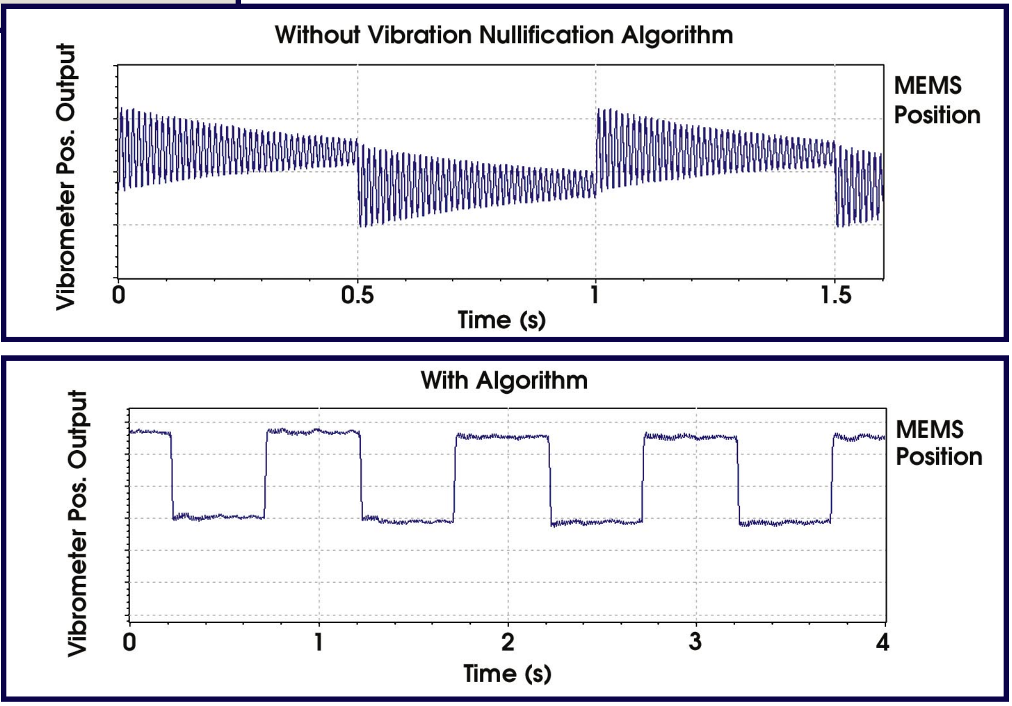


Figure 2. *Without a control scheme to nullify resonance, open-loop actuation of a MEMS micromirror inherently has a significant ringing problem, which could lead to long settling intervals and transient channel-crosstalk issues associated with the square-wave input. Courtesy of Applied MEMS Inc.*



systems (MEMS) — the time required for adequate settling grows exponentially (see sidebar on page 62). Another approach then becomes necessary to optimize the process. In such cases, the solution often lies in the control strategy employed with the system controller. More precisely, it may lie in the use of a control algorithm designed specifically to address motion control of systems with unwanted dynamics such as vibration.

Controlling dynamics

Working with a patented[1] control algorithm called InputShaping®, Polytec PI engineers have improved throughput by up to three orders of magnitude in certain motion-control applications, such as those required in the manufacture of fiber Bragg gratings, by eliminating settling dwells and allowing more aggressive motion profiles. The technique also can help improve the actuation speed for optical MEMS. Originally developed at Massachusetts Institute of Technology in Cambridge and commercialized by Convolve Inc. in New York, it is an integrated option for Polytec's digital piezo-positioning controllers.

Although the software code supporting the algorithm is complex, the concept it encapsulates is fairly simple. The software developers based the algorithm on the fact that, within almost any system prone to vibration, a motion transient will further excite the vibration. In most systems, scientists can characterize such vibration by measuring one or more of the frequencies excited by the motion transient. Based on this information, it is possible to generate a modified command signal to move the system at the maximum rate that does not excite vibrations. This theory holds true whether the vibration is an element of a production process used to manufacture photonic components or simply a side effect of movement by a component such as a MEMS device.

Consider the manufacture of fiber Bragg gratings. Each is simply a diffraction grating fashioned deep within a fiber or waveguide through interferometric optical exposure. To improve the spectral characteristics of the finite-length grating, the grating transitions must be apodized through nanometer-precision scanning motions of optics in the exposure apparatus. This demanding process produces a simple, compact, rugged, entirely passive device capable of precisely isolating a single wavelength.

However, as service providers begin to demand that a fiber carry more and more channels, the selectivity of the gratings must keep pace. Inaccuracies from vibrations of structures throughout the manufacturing tooling begin to influence the outcome more dramatically. Not only must the positioners in the tooling perform to nanometer-scale levels, but a method also must be in place to suppress all unwanted motions in other components. Air-isolation tables address ambient disturbances, but resonances driven by the scanning can still take hundreds of milliseconds to damp out — an unacceptable throughput penalty.

Optimizing MEMS motion

Using the control strategy patented by Convolve engineers, it is possible to nullify structural resonances from manufacturing tooling such as the closed-loop piezo stage used for high-throughput, nanometer-scale mask position modulation. Benefits can include higher process throughput as well as optimized grating fidelity for narrower channel width and improved system efficiency (Figure 1).

In the case of optical MEMS de-

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Feeding off the Motion Transient

There is no way around the fact that vibrational physics translates into problematic process throughput as device tolerances tighten. One common solution to vibration damping is simply to increase dwell times to allow things to settle down. The problem is that, the tighter the tolerances, the longer it takes for adequate settling. After a motion, the amplitude of the resonant ringing of each element in a structure scales as $e^{-t/\tau}$, where τ is the time constant for each element's resonant characteristics. For structures with damping characteristics typical of precision-motion subassemblies, $\tau \sim (\omega_n \zeta)^{-1}$ where ω_n is the resonant angular frequency and ζ is the damping ratio for the resonance. The parameter is commonly defined as the ratio of the damping for the resonance vs. critical damping ($\zeta = C/C_c$) and varies from 0 (no damping) to 1 (critical damping).

Time constant τ for various damping coefficients, ζ, and resonant frequencies, ω_n

F_{res} (Hz)	ω_n (rad/s)	ζ	τ
75	471.24	0.0005	4.244
		0.001	2.122
		0.005	0.424
		0.01	0.212
		0.05	0.042
		0.1	0.021
150	942.48	0.0005	2.122
		0.001	1.061
		0.005	0.212
		0.01	0.106
		0.05	0.021
		0.1	0.011

vices such as switches, cross connects, mirrors and attenuators, the compactness of the Input Shaping algorithm and its robustness relative to unit-to-unit variations make it practical for embedding into device controllers. The goals of this control scheme include:

- Optimization of MEMS elemental positioning times.
- Elimination of settling intervals in open- and closed-loop actuation.
- Prevention of parasitic excitation of adjacent elements in MEMS arrays.
- Bandwidth increase (gain boosting) in closed-loop actuation, with the goal of eliminating overshoot and ringing issues in underdamped actuation.

The benefits

One way to examine the benefits of such a control strategy involves inspection with a laser Doppler vibrometer (Figure 2). In recent testing, scientists studied vibrometer displacement and spectral measurements before and after implementing the algorithm in series with the position-command signal for an open-loop MEMS switching/scanning element. In this example, the implementation process was a simple one, requiring a straightforward measurement of the resonant characteristics of the MEMS device with the vibrometer. This also helped to define the real-time operating parameters for the algorithm. The outcome was the elimination of resonances of each micro-optical element, regardless of actuation profile, as well as elimination of the resonant reaction of neighboring MEMS elements.

In closed-loop actuations, it may also be possible to significantly boost proportional and integral gains, with the control scheme addressing the overshoot and oscillation about the terminal position that are otherwise characteristic of overboosted and underdamped applications. This can further improve the switching throughput of many devices compared with critical damping. Even better, the elimination of resonant behavior may eliminate the need for closed-loop actuation in the first place, which could produce a significant cost advantage.

Regardless of whether the vibration problem is with the manufacturing process or a MEMS component, it is important to note that there is a fundamental difference between resonance nullification with the algorithm and active damping, alignment stabilization or other after-the-fact compensation of unwanted resonant behavior. In those situations, compensation occurs after the device is observed to have begun ringing, with the aim of counteracting the unwanted motion or extracting energy from the resonance and converting it into heat or storing it elsewhere in the system. These all take time.

The advantage of resonance nullification through an algorithm in the system controller is that it prevents energy from entering the resonant mode. Long-term, besides offering benefits to photonic component manufacturing processes, this control scheme has the potential to further address the uniquely nonlinear actuation physics of specific MEMS designs. ☐

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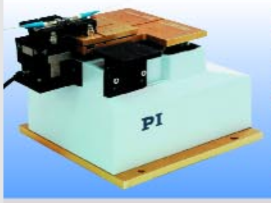

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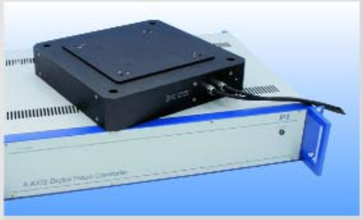

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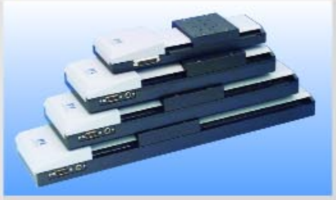

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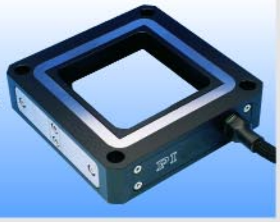

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