MAD CITY LABS INC.

Understand Noise At The Sub-nanometer Scale

Astronomers around the world were overjoyed in September 2015 when they got word that the Laser Interferometer Gravitational-Wave Observatory (LIGO) had picked up a sound from the distant universe. That sound was the noise of two black holes smashing into one another more than a billion light-years from Earth, and LIGO detected it by measuring the miniscule movement of a mirror as a gravity wave from the collision passed by.

Most everyday users of nanopositioners don't need to detect distant astronomical events, but they still must have devices sensitive enough for whatever task they are performing. Such users may perform more down-to-earth interferometry or try to point a laser beam with high accuracy. They might be interested in looking at single cells under a microscope or using scanning probe microscopy to characterize the surface roughness of a microchip. And to know whether their system is up to their particular task, they need to understand the inherent noise of their positioners.

Every positioner has some level of uncertainty in its position, some slight amount of movement that contributes noise to a measurement. The question is whether that uncertainty—also known as position noise—is tolerable for a given device and a given application. Most manufacturers of nanopositioning systems specify their noise, but for a customer to make an informed decision, they must have some understanding of what that noise specification means.

What's The Source?

The people performing high-precision nanopositioning tasks generally understand that vibrational noise coming from external sources can cause errors in their applications. Usually they'll place their equipment on air tables that isolate it from common environmental vibrations, and often they'll add an enclosure to block out noise caused by air currents or ambient sound. There can also be electrical noise from the electronics of the control system, caused by poor design or using the wrong type of power supply.

But even when all of these noise sources have been taken into account, the nanopositioner itself has some inherent noise that cannot be completely eliminated. That noise may be random motion of the device, or it may be driven by the resonant frequency of the nanopositioner. It must be understood so the user is sure he's getting accurate measurements.

A high-resolution nanopositioner usually has a range of motion of between 5 and 500 micrometers. It typically consists of a flexure-guided stage that is moved by ceramic piezoelectric actuators, along with a position sensor that provides a feedback signal to the control electronics. Each of these components produces some noise, and the intrinsic noise of the nanopositioning system is the sum of all those sources. Even if the job of the nanopositioner is to hold something still rather than move it over a certain range, it won't be absolutely still. The question becomes, is it still enough for what one is trying to measure?

Whatever resolution a particular application needs, the intrinsic noise of the nanopositioner has to be lower or it will swamp any signal. For instance, if you're trying to measure a surface feature that's 300 picometers high but the noise of the nanopositioner is on the order of 300 picometers, the measurement won't be reliable.

How To Measure Noise

Position noise might seem too small to measure. Low-noise amplifiers combined with low-noise position sensors produce an overall position noise well below the limits of precision instruments. Even interferometry can't reach the required level of accuracy in the subnanometer region. But as it turns out, noise can be quantified with noise power-spectrum analysis using fast Fourier transforms. Power-spectrum analysis is a well-known technique; the semiconductor industry employs it to specify voltage noise in operational amplifiers and transistors.

To test a nanopositioner, we drive its input with a reference signal, which is a sine-wave signal of known amplitude and frequency scaled to produce a small displacement. The output signal from the position sensor is continuously digitized as a fixed acquisition rate and for a fixed data-record length. The result is a data record that contains both amplitude and frequency information from the position sensor.

We then take that record and apply a fast Fourier transform, generating a power spectrum of the measured voltage versus frequency (Fig. 1). Because we know the amplitude and frequency of the reference signal, we can scale the spectrum we've acquired to reflect the noise-power spectrum of the nanopositioner.

What's shown is the peak-to-peak displacement of the system. Some nanopositioner manufacturers give noise as a single value, showing their root-mean-square (RMS) noise, which measures the average displacement. RMS noise makes the system's overall noise appear to be smaller, but it doesn't give any meaningful information about the actual position of the device and whether it's too great for a given application. It's important to know the overall noise floor values, the temporal performance, and what level of precision is achievable.

What's The Frequency?

It's also important to keep in mind that position noise is dependent on frequency. Positioning stages often have a frequency response programmed into them by the closed-loop feedback control. That response might be 100, 200, 500, or even 1,000 hertz. So the noise of the device at 10,000 or 100,000 Hz is irrelevant to how well it functions. What's important is the frequency at which the device is used. Say, for instance, the device has displacement of 2 nanometers at a frequency of 20 Hz. At that noise level, it cannot be considered capable of positioning to within 1 nm. A noise spectrum that plots the amount of noise over a range of frequencies will al-

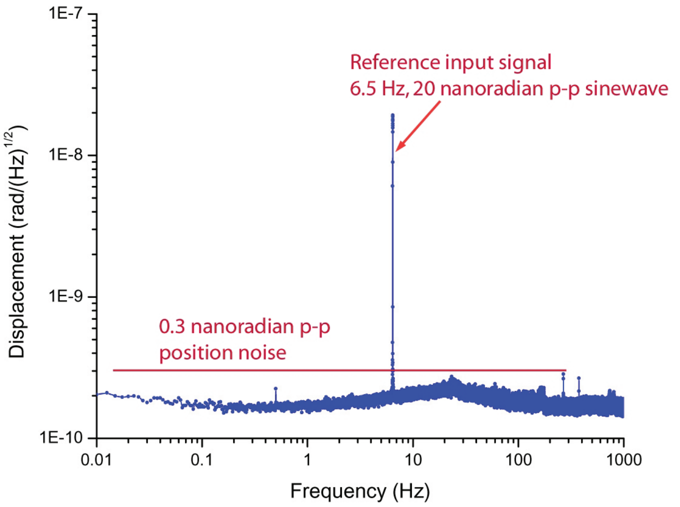

Fig 1. Noise power spectral density of Mad City Labs Nano-MTA2 with PicoQ® sensor technology. The figure shows a position noise floor of 0.3 nrad/√Hz.

low the user to evaluate whether the nanopositioner is appropriate for a particular application.

Some applications involve moving the nanopositioner over some distance. For instance, a user might build an atomic-force microscope to measure the surface roughness of a sample. That would involve dragging a measurement tip across the surface and seeing how much it is displaced vertically by features on that surface. The vertical position noise must be smaller than the vertical movement the tip will experience when it hits a bump or depression on the surface. In this case, the frequencies to be concerned with are the frequency at which the tip is scanned over the surface and the frequency of the vertical displacement.

Holding Still

In other cases, though, the aim is to have the nanopositioner hold something in place. There will still be some movement, but it will be very small. You'll need to know the frequency response at very low frequencies of the nanopositioner, perhaps a fraction of a hertz. So if the goal is to, say, hold something in position to within 50 picometers, the position noise at that frequency has to be lower than 50 pm/√ Hz.

Another factor to take into account is which part of the nanopositioner is producing noise, and how much. Nanopositioning systems can have as many as six axes, and it's important to separate the noise coming from different axes. If, for instance, you're measuring surface roughness, you'll be most interested in the vertical, or Z, axis. Noise in the X axis may not be as much of an issue.

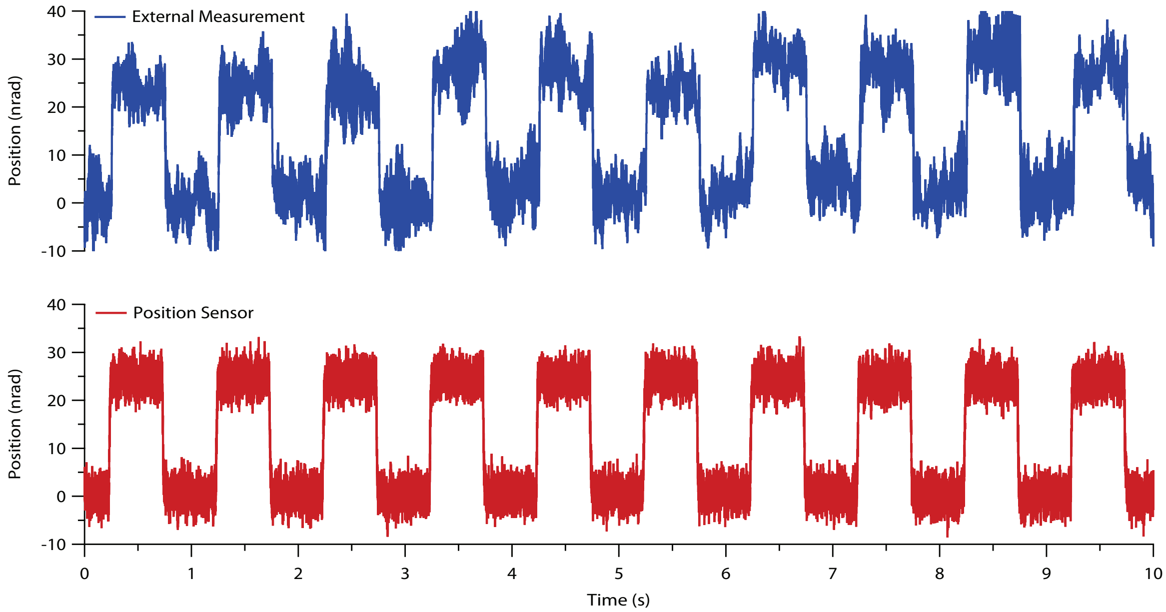

Fig 2. The Nano-MTA2 executing 25 nanoradian steps at 1 Hz. The external angular measurement (blue, top) correlates closely with the data obtained from the PicoQ® sensor output (red, bottom). Both position measurements demonstrate the ultra-low noise and high-resolution capabilities of the Nano-MTA2 nanopositioner.

So breaking down how much noise each individual axis contributes gives a more accurate picture of device performance.

The LIGO Case

The Nobel-winning LIGO experiment was one example of the importance of knowing whether a nanopositioner has sufficiently low position noise. LIGO is a giant interferometer, consisting of two laser beams bouncing off mirrors and meeting in an L shape, each in a tunnel 4 km long. As a gravitational wave passes through the system, it compresses space slightly, causing the length of one or both beams to change slightly, knocking them out of phase. The change in the spacing between the mirrors is a tiny fraction of the size of a proton.

The Mad City Labs' Nano-MTA2 fast mirror-steering nanopositioning system, equipped with position sensors and low-noise controllers, was used in one part of the experiment as part of the beam correction system. The device is a two-axis tilt/tip system with a range of motion of 2 milliradians per axis, a measurement of angle.

In a separate experiment (1), the Nano-MTA2 nanopositioning system was commanded to move in 25 nanoradian steps at a frequency of 1 Hz. The movement was measured by the position sensor and confirmed by an external experiment that looked at how much a laser beam was displaced (2) as the nanopositioner was moved (Fig. 2).

Making The Right Choice

Position noise is an important determinant of whether a nanopositioner provides the accuracy an application requires. In selecting a nanopositioning system, it's important to understand how much position noise is inherent to the system. That cannot be expressed in a single value, but should be shown as a spectrum that plots noise over frequency and separates the noise from different axes. Armed with such information, users can be sure they're getting a low-noise, high-precision system that meets their needs.

References

1. Technical note T-003 "High resolution steps for angular displacement using the Nano-MTA2", Mad City Labs November 2016.
2. M. Pisani, M. Astrua, "Angle amplification for nanoradian measurements," Appl. Opt. 45, 1725-1729 (2006). https://doi.org/10.1364/AO.45.001725

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