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NEWS RELEASE

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Note to Journalists: An electronic copy of the research paper is available from Emil Venere, (765) 494-4709, venere@purdue.edu. A publication-quality image showing chaotic behavior of the oscillating tip of an atomic force microscope also is available at http://news.uns.purdue.edu/images/+2006/raman-chaos.jpg

Purdue engineers solve chaos mystery in use of high-tech microscope

WEST LAFAYETTE, Ind. — Mechanical engineers at Purdue University have proven that the same sort of "deterministic chaos" behind the baffling uncertainties of the stock market and long-term weather conditions also interferes with measurements taken with a commonly used scientific instrument.

"The idea that chaos interferes with measurements in atomic-force microscopy has been sort of an urban myth over the years, but we have now proven this to be a fact," said Arvind Raman, an associate professor of mechanical engineering.

The findings will be detailed in a paper to appear online on Jan. 20 in the journal Physical Review Letters. The paper was written by mechanical engineering doctoral student Shuiqing Hu and Raman.

The engineers also have shown through a series of experiments precisely how much error is caused by the effects of chaos, information that could be used to help researchers make more accurate measurements with atomic-force microscopes.

Atomic-force microscopes are instruments used to take three-dimensional images of tiny structures for research and industry in fields such as nanotechnology, electronics, telecommunications and biotechnology. Researchers use the instruments to determine the features of objects and materials on the scale of nanometers, or billionths of a meter. The method works by passing a tiny cone-shaped tip close to the surface of an object, tracing its features. The tip is attached to a device called a "microcantilever," which resembles a diving board with the tip attached to the free end. The cantilever is caused to oscillate by the vibrating motion of a "piezoelectric crystal" that moves when voltage is applied to it. The force exerted by the crystal can be adjusted to increase and decrease how much the tip oscillates. The greater the vibration, the larger the "amplitude," or how far the tip moves each time it swings toward and away from the surface of the object being measured.

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As the cantilever tip oscillates up and down, its motion is influenced by forces, including van der Waals' forces, which exist between atoms. The van der Waals' forces become stronger as the tip gets closer to the surface. Information about the strength of the atomic force reveals how close the tip is to the surface of the object being studied. Researchers use this atomic-force information to position the tip extremely close to the surface. Then, as the tip scans the surface and encounters changes in contour, the entire microcantilever assembly tracks up and down to keep the tip's oscillating amplitude the same. The changing position of the cantilever is carefully monitored to reveal the topology of the surface of the object, yielding an image. This method for using the microscope is commonly referred to by researchers as the "tapping mode."

"For the method to work properly and yield accurate images that show features on the scale of nanometers, the microcantilever tip should always oscillate the same way, nice and smoothly like clockwork," Raman said. "But sometimes the tip suddenly begins oscillating chaotically, producing errors in the measurements."

Until now, researchers did not know why under certain operating conditions nanoscale features appear "noisy" and erroneous.

Hu increased the driving force of the piezoelectric crystal while the microscope was operating in the tapping mode to deliberately produce chaos. The research showed that increasing the amplitude of the microcanteliver by a specific amount resulted abruptly in chaotic oscillations. When Hu increased the amplitude again slightly, the oscillations returned to a normal, smooth motion. Increasing the amplitude further again resulted in chaos.

The experiments were conducted under various conditions, including inside an airtight chamber filled with pure nitrogen, eliminating water vapor, which could taint the results. Hu also analyzed data to detect chaotic behavior by using the same kinds of sophisticated software algorithms commonly used to identify chaotic patterns in the stock market.

"This is the first experimental proof that under some reasonable operating conditions these cantilevers can oscillate chaotically," Raman said. "We are not claiming that our findings answer all of the questions about what causes the chaotic behavior in atomic-force microscopy. There could be additional reasons for the chaotic behavior."

The errors resulting from chaos cause measurements to be off by only a few nanometers.

"We end this paper by saying that maybe this amount of error is negligible by today's standards because the average atomic-force microscope user is not measuring features as small as one or two nanometers," Raman said. "They are making measurements on the scale of about 1,500 nanometers, so if you are off by a couple of nanometers, no big deal.

"But some researchers are pushing the technology and trying to measure very carefully on the scale of two or three nanometers. Certainly, in the future, more and more scientists and engineers will be making measurements at this scale and the errors caused by chaos will no longer be negligible. These findings will be helpful in preventing chaos and reducing the errors."

The findings also identify which types of cantilevers are most prone to chaos, depending on what they are made of and how stiff they are.

"Two major practical results are that we now know what kinds of cantilevers to choose to avoid chaos, and we know the range of amplitudes that result in chaos."

Another important revelation, Raman said, is that the form of chaos observed is in the "deterministic" world of ordinary physics that governs everything from a baseball's trajectory to the motion of planets. Researchers had thought the microscope's sudden aberrant behavior might be caused by exotic forces associated with quantum mechanics, which describes the abstract inner workings of atoms.

Chaos usually is observed in large-scale phenomena, such as long-term weather conditions, the motion of objects in the solar system, sudden changes in the heart's rhythm or the operation of mechanical systems such as washing machines. In such cases, the chaotic behavior is caused by small, seemingly unrelated random events. This randomness has been described as the "butterfly effect," or the idea that small variations in the initial conditions of a system result in large changes in the long-term behavior of the system. Tiny changes in the atmosphere caused by a butterfly flapping its wings could ultimately combine with other random events to produce severe weather a year later thousands of miles away.

"You very rarely see chaos and nanotechnology mentioned together, but it's nice to know that chaos is not just something that happens on the large scale," Raman said.

The research was funded by the National Science Foundation and is associated with Purdue's Birck Nanotechnology Center at Discovery Park, the university's hub for interdisciplinary research.

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Related Web sites:
Arvind Raman: http://tools.ecn.purdue.edu/ME/Fac_Staff/raman.whtml
Birck Nanotechnology Center: http://www.nano.purdue.edu

IMAGE CAPTION:

Mechanical engineers at Purdue University have proven that the same sort of "deterministic chaos" behind the baffling uncertainties of the stock market and long-term weather conditions also interferes with measurements taken with an atomic-force microscope. The engineers also have shown through a series of experiments precisely how much error is caused by the effects of chaos, information that ultimately could be used to help researchers make more accurate measurements. These three images taken with an atomic-force microscope show the three-dimensional shape, or topology, of a flat sheet of a material called highly oriented pyrolitic graphite. The image on the far left shows how the image should look when the tip is oscillating normally. The two other images are examples of errors created when the tip suddenly starts moving chaotically. (Photograph courtesy of Purdue University School of Mechanical Engineering and Birck Nanotechnology Center)

A publication-quality photo is available at http://news.uns.purdue.edu/images/+2006/raman-chaos.jpg

ABSTRACT

Chaos in dynamic atomic force microscopy

Shuiqing Hu and Arvind Raman, Birck Nanotechnology Center and School of Mechanical Engineering

Chaotic oscillations of microcantilever tips in dynamic Atomic Force Microscopy (AFM) are reported and characterized. Systematic experiments performed using a variety of microcantilevers under a wide range of operating conditions indicate that softer AFM microcantilevers bifurcate from periodic to chaotic oscillations near the transition from the non-contact to the tapping regimes. Careful Lyapunov exponent and noise titration calculations of the tip oscillation data confirm their chaotic nature. AFM images taken by scanning the chaotically oscillating tips over the sample show small, but significant metrology errors at the nanoscale due to this “deterministic” uncertainty.