how it works

**WORCESTER POLYTECHNIC INSTITUTE USES A UNIQUE METHODOLOGY TO CHARACTERIZE SANDIA'S MEMS MICROENGINES.**

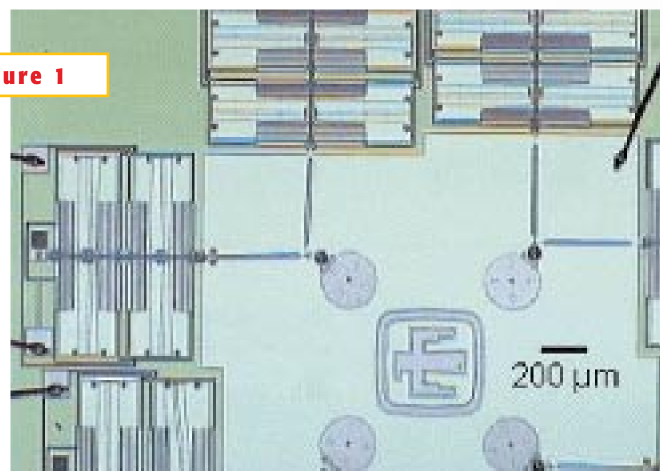
# MEMS micromotors rev up to 500,000 rpm

*By Bill Travis, Senior Technical Editor*

Under the direction of Professor Ryszard Pryputniewicz, WPI (Worcester Polytechnic Institute, Worcester, MA, www.wpi.edu) is developing advanced methods for materials analysis and characterization in subminiature structures. The vehicles for these developments are the various MEMS (microelectromechanical systems) from Sandia National Laboratories in Albuquerque, NM (www.sandia.gov). Pryputniewicz heads NEST (Nanoengineering Science and Technology) and CHSLT (Center for Holographic Studies and Laser micromechaTronics) at WPI. In characterizing the MEMS, WPI uses both analytical and experimental methodologies. Analytical models use a vector-mechanics approach to define kinematic and kinetic characteristics of the MEMS. The experimental methodology uses laser interferometry, which allows rapid measurements of the dynamic characteristics of the MEMS. Another experimental approach at WPI uses "nanoindentology," in which a tool with a minuscule bump creates a dent in the material under test.

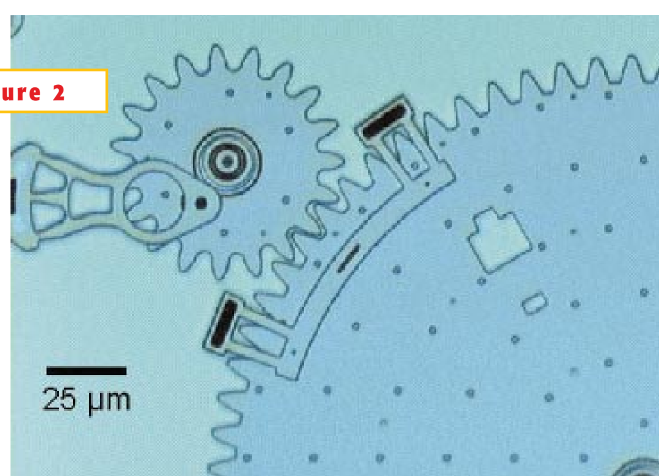
**Figure 1** shows an array of four MEMS microengines from Sandia. Each microengine comprises a 64-μm drive gear and a 300-μm output (load) gear. Two orthogonal linear comb-drive actuators turn the drive gear. The comb drives consist of one stationary set of fingers and one movable set. At rest, the fingers are in the as-fabricated position. Upon application of a voltage, electrostatic force causes the stationary set of fingers to attract the movable set.

Figure 1




**A Sandia microengine uses electrostatic signals to drive gears in a ratchet-like mechanism.**

Figure 2




**Note the 25-μm scale in this detailed view of the drive mechanism in Sandia's microengine.**

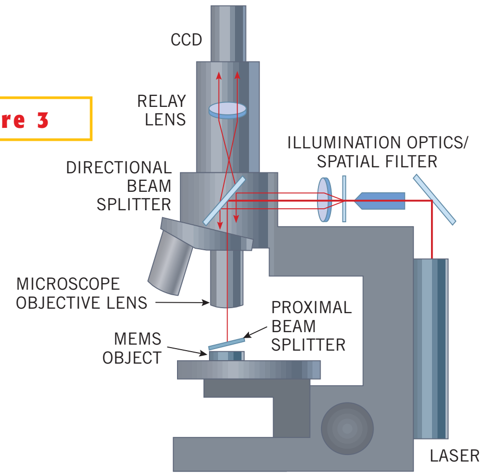
When the voltage disappears, elastic forces restore the position of the movable fingers. **Figure 2** shows details of the ratchetlike drive mechanism. WPI has characterized the microengines at speeds as high as 500,000 rpm; the MEMS can theoretically attain 1 million rpm. The limiting factor is out-of-plane wobble of the rotating parts. Typical out-of-plane (tilt) motion for the drive and output gears ranges from zero to ±462 nm and zero to ±514 nm, respectively. Out-of-plane motion can result in disengaging of the gears and inordinate wear, leading to premature failure of the microengine. It can also lead to undesired chattering of the mechanism.

WPI has developed an optical methodology to characterize the rotational motions of the drive and output gears. The technique allows visualization of the out-of-plane displacement gradients of an unbalanced rotating microgear. To complement the experimental method, WPI has developed analytical techniques to determine the estimated displacements, based on an analysis of manufacturing tolerances. These tolerances are currently on the order of 0.5 μm. Using the characteristic geometry of the microengine, WPI has determined the maximum out-of-plane tilts of the drive and output gear to be approximately 1100 and 500 nm, respectively. Although MEMS devices are relatively small, they are still larger than the wavelength of visible light. Thus, optical-interferometry methods are eminently practical for the measurement and test of the microengines. WPI has developed characterization techniques using an OELIM (optoelectronic laser-interfero-metric microscope).

## OPTO ANALYSIS YIELDS DISPLACEMENTS

In the OELIM methodology, a laser beam of collimated coherent light enters the system and impinges on a spatial-filter assembly consisting of a microscope objective and a pinhole filter (**Figure 3**). Lens L1 then collimates the resulting expanded light field. The directional beam splitter redirects the collimated light through the long-distance microscope objective lens to illuminate the object under test. The proximal beam splitter, placed over the object under test, tilts by a small angle with respect to the object. Consequently, from the observation point, you can view two intensity distributions: one of light reflected from the object and the second resulting from reflection from the bottom surface of the proximal beam splitter. The reflected light transmits back through the microscope objective lens, directional beam splitter, and the relay lens to the CCD camera. In the MEMS study, the wave fronts are planar, and thus interference fringes result when the proximal beam splitter is in the path. The CCD camera captures single-frame images that the computer then processes. These images yield a valuable qualitative insight into the motion of the microengine and its microgears. The images also provide quantitative measurements of displacement, using optical-phase measurements.

**Figure 3**




**Optical-interferometry techniques let you observe displacements in Sandia's MEMS.**

For OELIM tests of the microengine, the drive gear rotates 360° (one complete turn) in four steps of approximately 90° each. The input-signal frequency is adjustable to produce rotational speeds of the drive gear from zero to 250,000 rpm. To determine microgear displacements, you must first calculate the optical phase from the interference images. The method used at WPI uses a single interferogram of the microgear, taken at each of the four 90°-spaced positions. Once you determine the optical phase, you can calculate displacement using the known relationship between the optical phase and the wavelength of the laser light.

You can detect tilting of the microgear by observing interferograms of the gear in various angular positions. The changing number of fringes in the interferogram and the fringes' orientation show clearly that the microgear tilts out of its plane as the angular position changes during the rotation cycle. Measurements show that the maximum tilt of the drive gear is approximately 1030 nm. This figure agrees with a geometric analysis of the drive gear's cross section, taking dimensional tolerances into account. The OELIM technique allows displacement measurement with an accuracy of approximately 10 nm. WPI found that manufacturing tolerances, approximately ±0.5 μm, can lead to "play" between the microgear and its flanged hub. As the comb drives actuate to drive the microgear, the gear tilts out of plane as it revolves about its hub.

WPI uses vector analysis to determine the accelerations of all moving parts of the microengine. Newton's Second Law then yields the dynamic forces acting on the parts. The first step is to define the positions of all components. Then, differentiation of the position equations yields either linear or angular velocity. A second differentiation produces acceleration figures. WPI uses vector-loop equations to define the positions of the components. From the acceleration figures, it's possible to calculate the forces acting on the components. The calculations reveal that the forces on the drive-gear pin range from 4 nN at 6000 rpm to 27 μN at 500,000 rpm (**Figure 4**). These forces load the drive gear and make it wobble as it rotates around the shaft. As discussed, WPI uses OELIM methodology to experimentally observe this wobble.

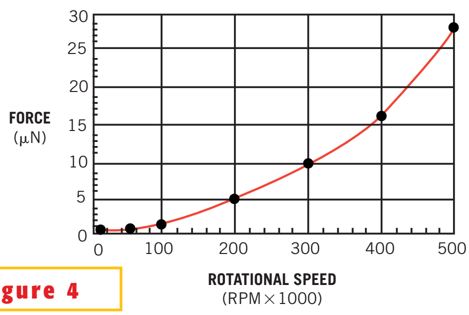



**Figure 4**

**The forces on the drive-gear pin range from 4 nN at 6000 rpm to 27 μN at 500,000 rpm.**

In addition to the microengine, WPI is collaborating with Sandia on other MEMS devices. In one MEMS, a microengine provides the drive to tilt a micromirror. Another MEMS from Sandia forms a microgyroscope, which incorporates accelerometers to measure position and motion in the x, y, and z axes. WPI also uses OELIM technology to characterize the microgyroscopes, with subnanometer accuracy. Using the results of WPI's tests, Sandia (or other manufacturing facilities, when the devices go into production) can improve MEMS' performance through manufacturing refinements. Venture Development Corp (www.vdc-corp.com) predicts that the MEMS market will grow from 1999's $2 billion to approximately $7.9 billion by 2004 (**Reference 1**). The advanced materials-characterization work taking place at WPI will no doubt contribute to that growth.□

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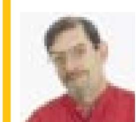

## Reference

1. Gulliksen, Eric J, "Microstructures technology (MST) and MEMS: An Industry and Market Evaluation," May 2000, Venture Development Corp.