

## Making Precise Resonators for Mesoscale Vibratory Gyroscopes

**It is essential to polish wafers to precise flatness and uniform thickness.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

An alternative approach to the design and fabrication of vibratory gyroscopes is founded on the use of fabrication techniques that yield best results in the mesoscopic size range, which is characterized by overall device dimensions of the order of a centimeter. This approach stands in contradistinction to prior approaches in (1) the macroscopic size range (the size range of conventional design and fabrication, characterized by overall device dimensions of many centimeters) and (2) the microscopic size range [the size range of microelectromechanical systems (MEMS), characterized by overall device dimensions of the order of a millimeter or less]. The mesoscale approach offers some of the advantage of the MEMS approach (sizes and power demands smaller than those of the macroscale approach) and some of the advantage of the macroscale approach (the possibility of achieving relative dimensional precision greater than that of the MEMS approach).

Relative dimensional precision is a major issue in the operation of a vibratory gyroscope. The heart of a vibratory gyroscope is a mechanical resonator that is required to have a specified symmetry

in a plane orthogonal to the axis about which rotation is to be measured. If the resonator could be perfectly symmetrical, then in the absence of rotation, a free vibration of the resonator could remain fixed along any orientation relative to its housing; that is, the gyroscope could exhibit zero drift. In practice, manufacturing imprecision gives rise to some asymmetry in mass, flexural stiffness or dissipation, resulting in a slight drift or beating motion of an initial vibration pattern that cannot be distinguished from rotation.

In the mesoscale approach, one exploits the following concepts: For a given amount of dimensional error generated in manufacturing, the asymmetry and hence the rate-of-rotation drift of the gyroscope can be reduced by increasing the scale. The decrease in asymmetry also reduces coupling of vibrations to the external environment. Mechanical thermal noise and electronic measurement noise and drift can also be reduced by increasing the size of the resonator and its associated sensors.

In the mesoscale approach, a resonator is fabricated from a silicon wafer. Central to the mesoscale approach is a

combination of (1) precise polishing of both faces of the wafer to form parallel planar upper and lower resonator surfaces and (2) dry reactive-ion etching (DRIE) to remove material from the sides of the resonator perpendicular to the upper and lower surfaces.

An experimental resonator was designed and fabricated following the mesoscale approach. Its frequency split (the difference between the natural frequencies of its two nominal orthogonal vibration modes — a measure of its asymmetry) was so small as to be undetectable at a resonance quality factor ( $Q$ ) of  $10^5$ , as observed in operation in a nominal vacuum with residual pressure of  $10^{-5}$  torr ( $\approx 1.3 \times 10^{-3}$  Pa). Throughout intensive experimentation, it was observed that keeping the thickness of the wafer as nearly uniform as possible was the main requirement for keeping the frequency split small, whereas the frequency split was not much affected by the side-wall roughness resulting from DRIE.

*This work was done by Eui-Hyeok Yang of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-30431*

## Robotic End Effectors for Hard-Rock Climbing

**End effectors emulate equipment used by human climbers.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

Special-purpose robot hands (end effectors) now under development are intended to enable robots to traverse cliffs much as human climbers do. Potential applications for robots having this capability include scientific exploration (both on Earth and other rocky bodies in space), military reconnaissance, and outdoor search and rescue operations.

Until now, enabling robots to traverse cliffs has been considered too difficult a task because of the perceived need of prohibitively sophisticated planning algorithms as well as end effectors as dexterous as human hands. The present end effectors are being designed to enable robots to attach themselves to typical rock-face features with less planning

and simpler end effectors. This advance is based on the emulation of the equipment used by human climbers rather than the emulation of the human hand. Climbing-aid equipment, specifically cams, aid hooks, and cam hooks, are used by sport climbers when a quick ascent of a cliff is desired (see Figure 1).

Currently two different end-effector designs have been created. The first, denoted the simple hook emulator, consists of three "fingers" arranged around a central "palm." Each finger emulates the function of a particular type of climbing hook (aid hook, wide cam hook, and a narrow cam hook). These fingers are connected to the palm via a mechanical linkage actuated with a leadscrew/nut.

This mechanism allows the fingers to be extended or retracted. The second design, denoted the advanced hook emulator (see Figure 2), shares these features, but it incorporates an aid hook and a cam hook into each finger. The spring-loading of the aid hook allows the passive selection of the type of hook used.

The end effectors can be used in several different modes. In the aid-hook mode, the aid hook on one of the fingers locks onto a horizontal ledge while the other two fingers act to stabilize the end effector against the cliff face. In the cam-hook mode, the broad, flat tip of the cam hook is inserted into a non-horizontal crack in the cliff face. A subsequent transfer of weight onto the end ef-

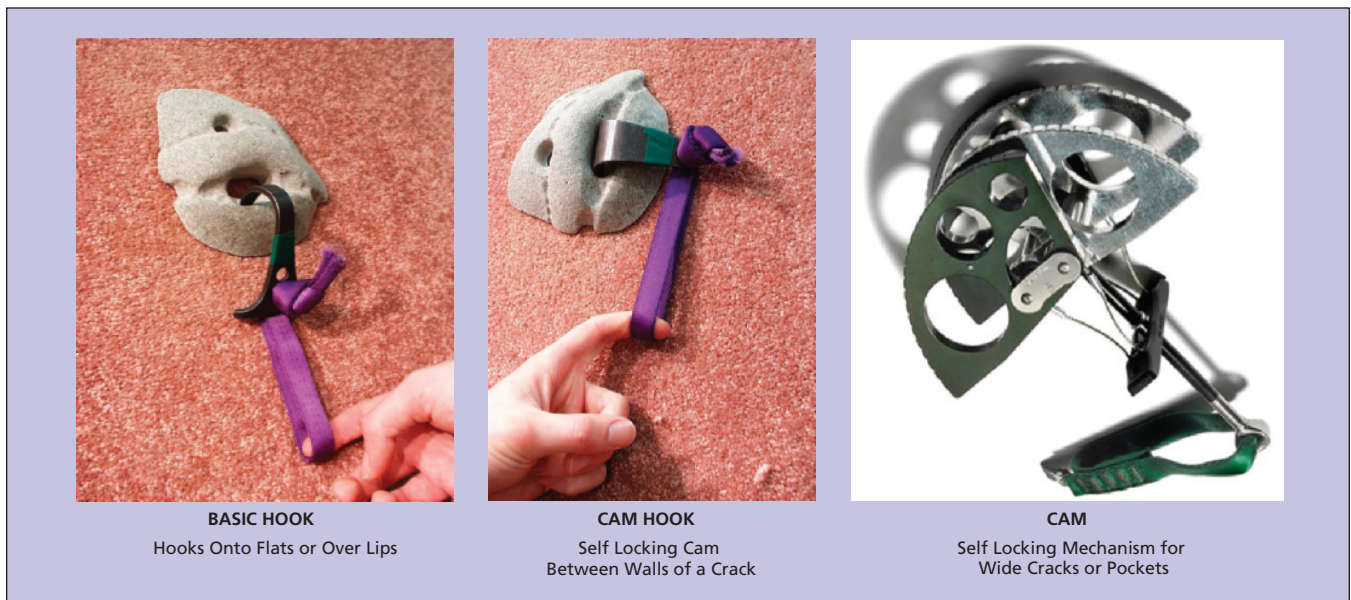


Figure 1. **Equipment Now Used by Human Rock Climbers** includes specially designed hooks, cams, and hook-and-cam assemblies. Elements of these items are being incorporated into robotic end effectors for rock climbing.

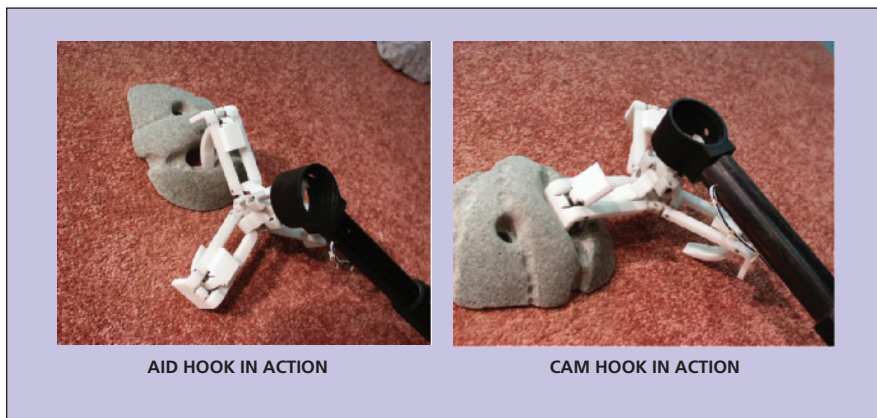


Figure 2. The **Advanced Hook Emulator** can function in a variety of modes. The aid-hook and cam-hook modes shown here correspond to the modes of operation of the conventional basic hook and cam hook, respectively, depicted in Figure 1.

factor causes the tip to rotate within the crack, creating a passive, self-locking action of the hook relative to the crack. In the advanced hook emulator, the aid

hook is pushed into its retracted position by contact with the cliff face as the cam hook tip is inserted into the crack. When a cliff face contains relatively large

pockets or cracks, another type of passive self-locking can be used. Emulating the function of the piece of climbing equipment called a “cam” (note: not the same as a “cam hook”; see Figure 1), the fingers can be fully retracted and the entire end effector inserted into the feature. The fingers are then extended as far as the feature allows. Any weight then transferred to the end effector will tend to extend the fingers further due to frictional force, passively increasing the grip on the feature. In addition to the climbing modes, these end effectors can be used to walk on (either on the palm or the fingertips) and to grasp objects by fully extending the fingers.

*This work was done by Brett Kennedy and Patrick Leger of Caltech for NASA’s Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-40224*

## Improved Nutation Damper for a Spin-Stabilized Spacecraft

*Goddard Space Flight Center, Greenbelt, Maryland*

A document proposes an improved liquid-ring nutation damper for a spin-stabilized spacecraft. The improvement addresses the problem of accommodating thermal expansion of the damping liquid. Heretofore, the problem has been solved by either (1) filling the ring completely with liquid and accommodating expansion by attaching a bellows or (2) partially filling the ring and accepting the formation of bubbles. The disadvantage

of (1) is that a bellows is expensive and may not be reliable; the disadvantage of (2) is that bubbles can cause fluid lockup and consequent loss of damping. In the improved damper, the ring would be nearly completely filled with liquid, and expansion would be accommodated, but not by a bellows. Instead, an escape tube would be attached to the ring. The escape tube would be positioned and oriented so that the artificial gravitation and

the associated buoyant force generated by the spin of the spacecraft would cause the bubbles to migrate toward the tip of the tube. In addition, when the spacecraft was on the launch pad, the escape tube would be at the top of the ring, so that bubbles would rise into the tube.

*This work was done by Mark A. Woodard of Goddard Space Flight Center. Further information is contained in a TSP (see page 1). GSC-14733-1*