MICROENGINEERING

Macro Power from Micro Machinery

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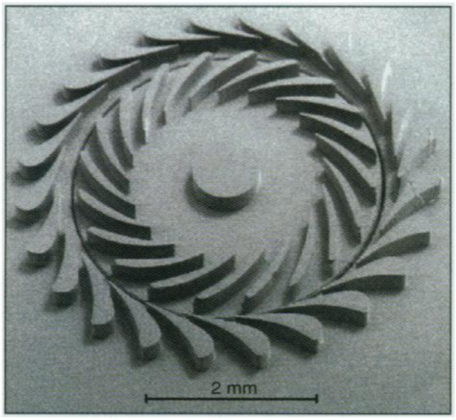
Richard Feynman, in two famous lectures (*1*), confessed to being fascinated with the idea of very small motors and machines, but also regretted that he didn't know what such "infinitesimal machinery" might be good for. In jest, he suggested that micromachines could be used in a child's game called "stab the paramecium."

Technology for the microfabrication of freely moving parts was developed in the mid-1980s, beginning with a Bell Labs microgear spun by an air jet (*2*), and electrostatic silicon micromotors (*3*). Applications in micropositioning of optics (*4*) have begun to appear. In parallel, development work has begun on miniature heat exchangers (*5*), small fluidic devices of various types (*6*), and recently, small chemical reaction chambers (*7*). So an answer to Feynman's question, "What might these machines be good for?" is beginning to emerge, albeit for relatively low-energy and low-power applications.

Within the past 2 years, a careful scaling study of high-speed, rotating turbomachinery has shown that suitably designed microdevices are actually remarkably promising (*8*). A conventional, macroscopic gas turbine generator, which can drive machinery such as an electric generator, consists of a compressor, a combustion chamber, and a turbine that is driven by the combustion exhaust and powers the compressor. The residual enthalpy in the exhaust stream provides thrust. A large-scale gas turbine with a 1-m-diameter air intake generates power on the order of 100 MW. When such a device is scaled to millimeter size, tens of watts would be produced, provided that the power density can be maintained. The realization of such an infinitesimal thermal machine requires the development of three microscale technologies: rotating machinery, combustors, and high-temperature material fabrication.

The key to achieving high-power density in both fluid and electrical rotating machinery is high peripheral speed. High speed in rotating machinery implies high centrifugal stress. In conventional practice, rotor speed is constrained to several hundred meters per second by the strength-to-density ratio of high-temperature metal alloys. However, microfabricated microelectronic materials have few defects and are thus quite strong. Also, their density is only 50% that of superalloys. Thus, compared to macroscopic materials, they have a superior strength-to-density ratio and so can be spun to high speeds without the risk of fracture (*9*). High rotating speeds also require low-friction bearings. Here the cubic scaling of volume, hence mass, combined with the quadratic scaling of areas (the so-called "cube-square law") means that the surface area–to-weight ratio of a rotor is large at small scales, implying that miniature air bearings can support large loads. Preliminary research in this area is quite promising.



The little engine that could. Electron micrograph of a 4-mm-diameter silicon microturbine. [C. C. Lin and M. A. Schmidt]

A combustor of a scale compatible to microrotating machinery may seem challenging at first because chemical-reaction times are invariant with size. However, the time required to mix the fuel and air is a major component of the total combustion time for conventional turbines, and these mixing times do scale. Indeed, a 2-mm-long combustion chamber suitable for turbine use has been recently demonstrated (*10*).

The figure shows a radial inflow turbine 4 mm across made from silicon, using deep reactive ion etching, a relatively new fabrication method. With minor changes in the airfoil shapes, the same device will function as a centrifugal compressor. Calculations show that such a turbine driving an electrostatic induction generator of similar size will supply tens of watts of continuous electric power. When made of refractory material, like silicon carbide, and combined with the compressor and combustor, a complete gas-turbine generator of under 1 cm^3 can be realized delivering as much as 50 W of electric power, or 0.2 N of thrust. The energy density of hydrocarbon fuels is so high that an equivalent mass in this technology can deliver 10 to 30 times the energy of even the most advanced battery materials.

There is also a remarkable benefit that derives from the cube-square law: If the power per unit airflow remains constant, then, because the airflow scales with the square of a linear dimension whereas the mass scales with the cube, the power-to-weight ratio would increase linearly as the size is reduced. Detailed calculations indicate that the scaling is not quite this dramatic, but a millimeter-size engine would have a thrust-to-weight ratio of about 100:1, compared to 10:1 for the best modern aircraft engines. This level of performance may have profound implications for flight vehicles. Of course, unless large arrays of such microdevices are used, vehicle masses would have to be constrained to a few tens of grams. This is a little small for most passengers, but there is now serious interest in sensor-laden microairplanes (*11*). And, as an astute child of one of the authors recently noted, 1400 of them working in parallel could levitate his skateboard.

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