Surface Tension Rules the Subminiature World of MEMS

By David Brown

One of the biggest challenges facing researchers who design machines on a subminiature scale is visualizing a world in which some of the most fundamental forces don't seem to work the way they do on a human scale.

Dominated by surface tension — the seemingly insignificant force that holds soap bubbles together — objects that appear to be almost weightless cling to each other like iron filings to a magnet. It is a world in which objects are unfazed by falls from heights a thousand times their own, but can be easily consumed by a single droplet of water.

Actually, there is nothing going on at the subminiature scale which can't be explained with relatively simple arithmetic, according to Chang-Jin (CJ) Kim, one of the world's leading researchers in the area of micro electro-mechanical systems (MEMS) and a professor of mechanical and aerospace engineering.

So why does surface tension become so great and inertia so inconsequential at these dimensions?

As an object's size decreases, so does its volume. Volume is proportional to weight and inertia. So as an object's size decreases, its volume decreases by a power of three — and so does inertia. Because surface tension decreases in direct proportion to the object's length, any reduction in surface tension is relatively small. So as size goes down, surface tension decreases only by a power of one, while inertia drops by a power of three.

In the subminiature world of MEMS, objects are a million times smaller! So the differences are sufficiently skewed to make thinking in this scale extremely difficult.

On an intellectual level, engineers have long been aware of this shift which makes surface tension the leading force and inertia all but irrelevant on a subminiature scale. Conceptualizing those problems, however, is another matter because "we don't live at that scale, so we never had a reason to develop engineering for that ergonomics," as Kim put it.

For inspiration, researchers like Kim turn to nature where, he said, there are an "abundance of examples."

"Nature is a very good example of how things should be designed," Kim said. "Certain kinds of animals are very well designed so they will survive."

Only about a millimeter in length, the ant is on the borderline between our world and the subminiature domain. So some of the characteristics of the subminiature world can be observed in ants. Once you cross the one-millimeter scale, the force of inertia becomes negligible and the adhesion forces become very strong — which explains why insects are able to crawl up walls.

A fall from a table — which is about a thousand of times its height — has little effect on an ant. That's because the force of inertia is smaller than the force that holds the insect's body together. Contact with a droplet of water, however, is to be avoided at all costs. The surface tension of the water droplet so exceeds the ant's strength, it would be impossible to separate itself from the droplet.

Yet the same insect can lift ten times its own weight. Again, Kim said, this is because of the scale in which it lives. "If our bodies could become as small as an ant, we could lift a hundred times our weight," Kim said.

"Would we design automobiles the way we do now if we were smaller than ants?" Kim wondered.

As a matter of fact, one of the first exercises for students in Kim's introductory classes is to review the movie *Antz* and determine which events are possible and which are merely fanciful.

But the surface tension phenomenon has not always been well understood. Surface tension, in fact, was seen more as a major problem when researchers first begun designing MEMS devices. If there was the slightest amount of moisture present beneath cantilever beams, surface tension would pull the beam down to the substrate, permanently welding it in place.

“In the beginning, we were designing all these things based on our own experience,” Kim said. “We did not design things with surface tension considered.” The first micro motors, in fact, could be rendered inoperative by the surface tension present in a single drop of water. Because at this scale, surface tension is the force “that dominates everything.”

This makes the design of mechanisms for those tiny dimensions “very hard to conceptualize,” Kim said. Researchers who remain confined by conventional engineering, he said, find it nearly impossible to solve problems in micro scale.

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But the forces, which dominate the subminiature world, can also be harnessed to solve problems. For example, former graduate student Fan-Gang Tseng took advantage of surface tension to improve the quality of inkjet printers. Tseng used the strength of a tiny drop of ink as a check valve [See *Ingeniare*, 1999].

But the dream of researchers like Kim who work in the micro environment is to use the same forces which rendered earlier micro motors inoperative to actually create motion.

“To be able to do that,” he said, “you have to be able to control surface tension.”

Surface tension can be used to create motion by increasing it at one point and decreasing it somewhere else, Kim said. This can be accomplished by adding a surfactant (such as soap, which lowers surface tension), raising the temperature at one point (which decreases surface tension) or by applying an electrical potential.

The first method — adding surfactant — is rather impractical because it would require an endless supply of surfactant.

Even though surface tension can be decreased by increasing temperature, Kim said, it is not a particularly efficient method.

The most efficient method of controlling surface tension, according to Kim, is to apply an electrical voltage. This method is also quite compatible with the MEMS environment because it is easy to create small electrodes. Using this approach, Kim and his researchers have created a miniature electric motor.

The motor consists of a circular micro channel about two millimeters wide, filled with an electrolyte and a small amount of liquid metal. Voltage is applied across one segment of the circular channel, creating a “surface tension gradient” along the length of the liquid metal. The difference in surface tension is what pushes the liquid metal around the channel.

The channel contains a thin layer of electrolyte, consisting of water and a minute amount of acid. Because the layer of electrolyte is very thin, its resistance is extremely high. Although the amount of power needed to operate the motor is only about one microwatt — virtually no consumption of energy — it spins at 420 revolutions per minute.

As a motor, the mechanism has a distinct disadvantage. There is not any way of connecting a shaft to the motor to transmit the motion and do useful work. However, Kim said it may find a use in the “pico” satellites of the future. In space, the motion of the liquid metal would cause the satellite to move in the opposite direction.

But for now, Kim said, “we should consider this more a driving mechanism than a motor.”

Kim said other MEMS researchers have been aware of this mechanism for 10 years. Although similar motors could have been constructed on a larger scale, these larger motors would be extremely unstable. The slightest vibration would disturb the liquid because these devices would also be so susceptible to inertia. Miniaturizing the motor, how-

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ever, decreased the effects of inertia and produced a device that is far more stable.

"We found out this mechanism actually works even better when you miniaturize it." Not only is it more stable, but the mechanism itself works more effectively.

As Kim pointed out, this is "miniaturizing for the right reasons," noting that people who do not fully appreciate the peculiarities of the subminiature world often attempt to miniaturize mechanisms, only to stumble onto unexpected problems.

Along with the inability to perform useful work, the miniature motor Kim designed has another serious drawback. It requires two separate liquids.

Now, Kim said, he wants to take another leap forward with an even newer mechanism.

The new mechanism Kim is developing would be used to move just a single droplet. But unlike the MEMS motor, which uses an electrolyte to move a liquid metal — making it a two-liquid system — the new mechanism would use only one liquid. And, instead of liquid metal, the device would be capable of moving *any* liquid. Kim readily admits this is far more challenging. One purpose of the new mechanism is to speed up DNA analysis.

Cracking the genetic code requires analysis of millions of samples of liquid containing the target DNA. Technicians deposit, or "print," DNA samples on glass slides, one sample at a time. Although dexterous technicians are capable of handling as many as a dozen applicators at a time and robotic arms can print a hundred droplets per minute, Kim's device would produce hundreds of samples with each printing.

"Obviously, with MEMS, you can probably make hundreds of droplets at a time if you miniaturize the whole thing," Kim said. And that's what he and his co-investigator, Dr. Stanley F. Nelson, an assistant professor in the School of Medicine, are attempting to do. DNA material would be supplied to multiple applicators using a mechanism similar to the one that drives the miniature motor.

Although immensely useful, Kim said, this is just one of dozens and dozens of ways this technology could be applied to a wide variety of applications in biomedical engineering. All of which is only possible because of the seemingly strange way nature behaves in the subminiature world of MEMS.