ACTUATORS AND THEIR MECHANISMS IN MICROENGINEERING

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The subject of actuation in microengineering is an expanding area of study. Many aspects need to be considered; the actuation mechanism, how well it scales to the micro level, the materials involved, process compatibility, reliability, and comparison with alternative techniques are all criteria in reaching a final judgement.

Capacitive

Electrostatic drive systems have a strong position in silicon microengineering. The arguments put forward for capacitive actuation are familiar: compatibility with CMOS processes and materials, little temperature dependence and a surface area law that becomes more powerful as device dimensions shrink (area/volume ratio increases). And, compared to electromagnetic actuators, capacitive systems are lightweight, need no external components and consume little power. In every application two electrodes are separated by an air gap. One electrode is usually fixed, and the other is free to move. A potential difference applied across the air gap will attract the free electrode to the fixed one, with a force proportional to the square of the electric field. This force will always attract, and so cannot be used, for instance, to increase the electrode spacing. Because of the square dependence, making the air gap narrow is very advantageous: typical values are in the 2 - 5 μm region.

Several points should be noted with regard to electrostatic actuation: the first is that it is material independent, and purely a dimension and voltage effect. Also, if an ac signal is used, the attractive nature of the force on both half-cycles means that the free electrode will be driven at twice the signal frequency. In addition, as an electrode deflects, the separation decreases and the force increases. The electrode separation will tend to become spatially non-uniform: this will be true for any structure, the bending of which will depend on the end clamping mechanism. Hence calculations of the forces involved will need time and distance-dependent integration.

Because of the attractive nature of the force a free electrode will keep bending until it is held in balance by an axial tensile load: if the drive voltage exceeds a certain value called the pull-in voltage, then the electrode will deflect all the way to touch the substrate. Careful positioning of the electrodes is needed to prevent electrical shorts and to allow the original relative positions to be restored. It would be expected that breakdown fields in the separation region will be high, about two orders of magnitude greater than those normally associated with air gaps, if the separation can be limited to less than 5 μm (the Paschen effect). Unfortunately, this has not always proven to be the case in practice. In any case the electrode gap should ideally be in a vacuum (unless the actuator is a pump) because energy will be dissipated in moving the air in and out of the electrode spacing (the squeeze film effect).

Another point to note regarding this type of actuation is that electric fields interact with most materials, meaning that electrostatic actuators may need greater environmental isolation than other techniques; magnetic fields only interact with ferromagnetic materials, for instance. Also, the unwanted ability of electrostatic fields to attract dust, and their adverse effect on CMOS circuitry, is well known.

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Electromagnetic

A common form of magnetic actuation is based on the Lorentz effect. This method is ideally suited for large electromagnetic applications, but in microengineering the cross-sectional area of the conductors (and hence the current passed) reduces as the square of the scaling factor; there is a further linear reduction in the length of the conductor, making the force produced reduce as the cube of the scaling factor. Because of this, magnetic actuation becomes quite weak on a microscale, unlike capacitive actuation. Hence many devices incorporate a solenoid to increase the level of actuation. Material issues also play a part: the flux density of the permanent magnet and the current carrying capability of the conductors need to be maximised.

Actuation control is via current rather than the preferred parameter of voltage. A large force means a high current, leading to problems of power consumption and dissipation. However, low voltages have an advantage when it comes to battery operation. In addition, magnetic actuation does not suffer catastrophic field breakdown, can cause movement in anti-parallel directions, and is tolerant to dust, humidity and surface topography.

Piezoelectric

Piezoelectricity is a property of insulating materials where an applied voltage generates an external stress. The force produced is quite large, the response times short, and efficiencies are high if the leakage currents and hysteresis effects are kept under control. However, the fractional stroke (dispalcement per unit length) is quite small, typically being no more than 0.2%. Piezoelectricity is a phenomenon that is highly material dependent: the molecules must be non-symmetric with respect to their charge distribution, and they also must be polarised. Spontaneous polarisation occurs in some materials, but most deposition methods and materials used in microengineering mean that initial poling must be carried out by heating the material above its Curie temperature, and then cooling in a strong electric field. Increasing use is being made of titanate materials, in particular PZT (lead zirconate titanate). This is very popular because of its ability to be deposited from a solution (the sol-gel process). The great interest in sol-gel has come from the fact that a planar structure can be achieved without the need for air gaps between electrodes. In addition, when optimised the piezoelectric process can provide a much greater actuation force than a capacitive system. Problems remain, however, in turning theoretical predictions into reliable applications, most notably in the uniformity of material deposited via the sol-gel process. An additional issue is that the piezoelectric coefficients are direction and temperature dependent.

Magnetostriction

The magnetostrictive effect is a similar dimension change under the influence of a magnetic field. For actuators to use this effect, a material with a low anisotropy constant must be chosen. The intrinsic, zero field domain structure of the material must also be considered. Magnetostrictive materials promise fractional strokes comparable to piezoelectrics, but with a much greater force; multilayer systems are being used to achieve a large stroke whilst maintaining magnetic softness. Response times of this type of actuation mechanism are short.

Electrostriction

This is also an applied electric field effect, and the response observed is dominated by electrostatic forces generated by free charges on the contact electrodes. On application of a voltage, unlike charges on the electrodes attract each other, and like charges repel. The resultant electrostatic forces compress and stretch the film. Unlike the piezoelectric effect, the force produced is proportional to the square of the applied field. Another difference is that piezoelectrics polarise under an applied pressure, whereas electrostrictive materials do not.

The problem of small deformations is common to electrostrictive, piezoelectric and magnetostrictive actuators. However, many new materials, in particular polymeric ones, are reaching the market as electrostrictive material, and which can produce a fractional stroke of around 4%. The technique does look attractive when compared to capacitive actuation; a polymer of high dielectric constant enables a high field strength to be maintained, the actuation force is linearly proportional to the dielectric constant and accurate alignment is not essential.

Thermal

This mechanism works on the principle that heat applied to the top of a beam will diffuse down through the structure to create a temperature gradient. Differential thermal expansion of the material will then introduce a mechanical moment to bend the structure. The heat may come from a resistive element or a high intensity light source. A greater bending moment may be achieved by using a bimorph arrangement, i.e. the structure is made of two materials with different coefficients of expansion; because of the high value of this parameter when using aluminium, this metal has been a popular choice for bimorph structures.

This is a very simple actuation mechanism, which can be incorporated quite readily into any structure. Drive voltages are low and large deflections can be produced. The dynamic behaviour of thermal excitation has always been a problem, however, because of the need to dissipate the residual heat from the previous cycle before the next can be implemented: hence operating frequencies tend to be low compared to other mechanisms.

Shape Memory Alloy (SMA)

The shape memory effect occurs in certain alloy materials such as TiNi. SMAs are plastically deformable materials that, on heating to the appropriate temperature, change their crystal structure: in the form of a wire this results in the SMA shrinking with temperature. On passing sufficient current, a transition temperature is reached and the SMA wire undergoes a phase transition to its unstretched state. Air cooling back through the transition temperature allows the SMA to regain its original length. Frequency responses are slow, with heat dissipation limitations similar to those on thermal actuation. A more fundamental limiting effect is the low efficiency. The shape memory effect is a heat driven phase change, and as such it will be limited to Carnot efficiency. Practical shape memory actuators operate at 5% efficiency or less.

Conclusions

There are many different types of actuation mechanisms used in microengineering. None has dominance over any other, and the choice of mechanism is a balance between many different factors: Table 1 shows a comparison of techniques discussed in this paper[1], with some typical results obtained.

Actuator	Fractional Stroke (%)	Max. Pressure (MPa)	Max. Energy Density (J/cm^3)	Efficiency	Speed
Electrostatic	32	0.025	0.004	High	Fast
Electromagnetic	50	0.10	0.025	Low at low speeds	Fast
Piezoelectric	0.2	35	0.035	High	Fast
Magnetostrictive	0.2	70	0.07	Low at low speeds	Fast
Electrostrictive	4	0.21	0.032	High	Fast
Thermal	50	10	25.5	Low	Slow
SMA	8	400	16	Low	Slow

Table 1.

References

1. R Kornbluh, R Pelrine and J Joseph, "Elastomeric Dielectric Artificial Muscle Actuators for Small Robots", Proc. 3rd IASTED Int. Conf. on Robotics and Manufacturing, Cancun, Mexico, June 14-16, 1995.