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Review

Piezoelectric ultrasonic micro/milli-scale actuators

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ABSTRACT

A growing demand for actuators with a volume of less than 1 mm^3 has driven researchers to produce a varied range of micro/milli-scale designs. By examining the underlying physics of the actuator operation we are able to demonstrate why piezoelectric ultrasonic actuators have the greatest potential to meet this need. Moreover, it allows us to create a new classification system for piezoelectric ultrasonic actuators, affording us a better understanding of the core characteristics of each class of actuator, which class is most suited to various applications, and highlights potential areas of future research.

Contents

1. Introduction

There is growing demand for actuators with a volume of less than 1 mm^3. This need has been reported across the micro-robotics industry [1] and the medical profession [2,3]. Despite such varied fields of use, the core characteristics required of actuators at millimetre and sub-millimetre scales are the same. Actuators at these scales require high output forces, accuracy, low response times, a simple design and simple operation. An understanding of how well myriad actuator classes may meet these requirements can be determined by examining the underlying physics of the actuator operation. The key focus of such an investigation is the force that is

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Table 1
Comparative scaling of motor driving forces (F is output force, L is characteristic length).

Motor class	Driving force	Scaling
Electromagnetic	Electromagnetic	$F \propto L^4$
Electrostatic	Electrostatic	$F \propto \frac{1}{L^2}$
Thermal	Mechanical strain	$F \propto L$
Osmotic	Osmotic effect	Dependent on many variables
ECF	ECF	$F \propto \frac{1}{L}$ minimum
Piezoelectric ultrasonic	Converse piezoelectric effect	$F \propto L$

used as the basis of design. This is the force that is produced by the stator and induces motion in the rotor/slider; hereafter referred to as the driving force.

Electromagnetic actuators are the most widely used of any design at the macro-scale, with small-scale versions also having been developed [4,5]. The driving force for an electromagnetic actuator relies on the interaction of the permanent magnets of the rotor, and the magnetic field induced by the current in the coil of the stator. The use of this non-destructive, non-contact force gives the electromagnetic actuator a high energy density, which compares favorably with most other actuator designs and has led to its wide spread use. However, as detailed in Table 1, the electromagnetic force poorly scales down [6] and the relative performance of an electromagnetic actuator becomes progressively worse as the length scale reduces to the order of millimetres. Moreover, due to the reduction in scale the electromagnetic driving force promotes an undesirable high speed, low force behaviour in the actuator. We concluded from this that the driving force that makes an electromagnetic actuator superior to most actuators in large-scale applications likewise makes it unsuitable as the actuator volume is reduced to the desired 1 mm^3.

The simple design of the electrostatic actuator has enabled researchers to produce actuators with diameters as small as 100 μm [7] and beyond [8], making them among the smallest practical actuators produced. This small size has led to some success in the field of micro-electro-mechanical systems (MEMS) [9], where size is of critical importance. As with electromagnetic actuators, electrostatic actuators use a non-contact force to create mechanical work. The force arises from the interaction between charged materials, and decreases with the square of the distance between the two charged bodies. The excellent scalability of the electrostatic force (the force increases with a reduction in size, see Table 1), is a major design advantage, and has allowed the development of the very small-scale actuators previously noted. However, the electrostatic driving force also leads to the disadvantages associated with these designs. Most importantly, the electrostatic driving force is weak when compared with many other forces used for actuation and in spite of excellent scaling characteristics, limits the output of electrostatic actuators. At the scales noted previously, the output torque is currently limited to approximately 10 pNm [7]. The electrostatic driving force also results in a nonlinear output for the actuator. This is particularly problematic at the end of the output range, where actuators can undergo ‘snap-down’. Moreover, the electrostatic driving force is very sensitive to the operating environment and actuator design. The maximum electrostatic field strength is strongly dependent on humidity and ambient gas content and the force performs best with actuator designs with low aspect ratios (large electrode surface compared to distance to travel). These deficiencies are less important for many MEMS applications, but limit the actuator’s use in most other areas.

Thermal actuators are another actuator design that have been employed in MEMS applications [10,11]. This type of design can be produced at scales comparable to electrostatic actuators, but have output forces in the order of micro-Newtons. In contrast to electromagnetic and electrostatic actuators, thermal actuators use a mechanical strain, rather than a non-contact force, as a driving force. Mechanical strain rates greatly vary depending on the type of material used, with smart memory alloys (SMAs) having significantly higher strain rates than regular metallic alloys. Regardless of the material used, the output can be magnified through clever geometric design with the actuator performance scaling linearly due to the inherent thermal characteristics. Although the thermally induced mechanical strain of these designs produces a high output force and scales well, actuators that use this driving force have two significant disadvantages. The first is that the driving force used results in a response time that is very slow when compared to alternatives, also affecting the actuator velocities obtained from the designs. The second is that the lifespan of the actuator may be limited due to the plastic strain arising from repeated cycling. With such characteristics, thermal actuators are most suited to applications that require large forces infrequently, such as micro-grippers.

Osmotic actuator designs utilise a different approach to creating motion [12] than those actuator classes already covered. The removal of the need for an electrical input is advantageous for some operating conditions and the design has obvious benefits for use with microfluidics. The driving force of an osmotic actuator is the increase in pressure within a vessel, leading to an expansion of an actuation diaphragm. The increased pressure is caused by one-directional flow of liquid across a semi-permeable diaphragm, driven by the osmotic effect. How well an osmotic actuator can be scaled is dependent on many factors, including the diaphragm material used and the concentration of the osmotic agent. Osmotic actuators have numerous disadvantages when applied to a broad spectrum of applications including:

- Slow response times, leading to low actuator velocities.
- Complex designs required obtain large, linear or rotational outputs.
- Problems with solute deposition, fouling and control.

Such drawbacks demonstrate that osmotic actuators are unsuitable for many applications. It is worthy to note however, that like thermal actuators, osmotic actuators have shown potential for use as micro-grippers.

A further somewhat unusual design is the design developed by Yokota et al. [13,14]. The driving force of these motors is the jetting phenomenon induced in an electro-conjugate fluid (ECF) when in the presence of an electric current. The motors use a rotor with vanes to harness the ECF jetting, producing the output rotation. Although the ECF jetting phenomenon is not yet fully elucidated, it has been demonstrated that motors designed using this driving force improve in performance as the scale is reduced [13]. Motors of these designs have good outputs, and excellent scalabilty, however, there may be difficulties in further reducing the scale of these motors below 1 mm^3[15].

The first piezoelectric ultrasonic micro/milli-scale actuators evolved from earlier larger scale piezoelectric actuators successfully used in cameras [16]. Since then, numerous small-scale actuators have been produced, including designs with dimensions of only a few millimetres [17] and nanometre positioning accuracy [18]. The driving force of a piezoelectric actuator arises from the converse piezoelectric effect, which converts a harmonic electrical input to a cyclic strain in the piezoelectric element. This driving force scales linearly with the characteristic length scale, potentially allowing useful amounts of work to be produced from small-scale actuators. This is especially true when the actuators are designed to operate near the mechanical resonance of the stator. In addition to good scalability, piezoelectric actuators have numerous other benefits for use as milli/micro-actuators. They include: