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Micro Piezoelectric Ultrasonic Motors

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Abstract. This paper reviews recent developments of micro ultrasonic rotary motors using piezoelectric resonant vibrations. Following the historical background, four ultrasonic motors recently developed at Penn State University are introduced; *windmill*, *PZT tube*, *metal tube*, and *shear-type* motors. Driving principles and motor characteristics are described in comparison with the conventional ultrasonic motors. Motors with 1.5 mm in diameter and 0.8 mN·m in torque have been actually developed.

Keywords: ultrasonic motor, piezoelectric actuator, standing wave motor

Introduction

The market research conducted in the middle '90's for 80 international electronic component companies provided a very intriguing demand for motors in these 10 years; that is, 5–8 mm size motors with reasonable efficiency, human-compatible force and inexpensive price. Regarding conventional electromagnetic motors, tiny motors smaller than 1 cm are rather difficult to be produced in principle with sufficient energy efficiency. Note that a wrist watch motor with a rotor diameter less than 1 mm ϕ still requires a relatively large (10 mm) coil for its activation, despite its low efficiency less than 1%. MEMS devices based on Silicon electrostatic actuation are too small in size with very small force, and do not endure against the component shaking/shock test. Ultrasonic motors whose efficiency is insensitive to size are considered superior in the mini-motor area. Following the historical background, four ultrasonic motors recently developed at Penn State University are introduced in this review paper; *windmill*, *PZT tube*, *metal tube*, and *shear-type* motors. Motors with 1.5 mm in diameter and 0.8 mN · m in torque have been actually developed. Some applications using these motors are introduced lastly.

Classification of Ultrasonic Motors

Historical Background

Electromagnetic motors were invented more than a hundred years ago. While these motors still dominate the industry, a drastic improvement cannot be expected except through new discoveries in magnetic or superconducting materials. Regarding conventional electromagnetic motors, tiny motors smaller than 1 cm long are theoretically difficult to produce with sufficient energy efficiency. Therefore, a new class of motors using high power ultrasonic energy, i.e., *ultrasonic motor*, is gaining wide spread attention. Ultrasonic motors made with piezoceramics whose efficiency is insensitive to size are superior in the mini-motor area. For example, a commercialized electromagnetic motor by Motorola with 7 mm in diameter and 16 mm in length can generate 0.075 mN·m in torque and 5000 rpm in no-load speed under an input power of 0.2 W, which is more than one order of magnitude higher than the

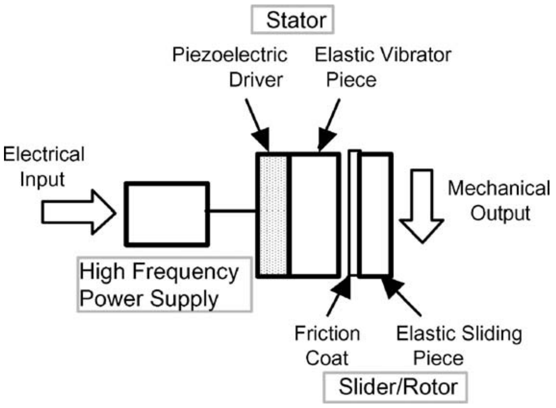


Fig. 1. Fundamental construction of an ultrasonic motor.

power required for our ultrasonic motors with similar specifications.

Figure 1 shows the basic construction of an ultrasonic motor, which consists of a high-frequency power supply, a vibrator and a slider. Further, the vibrator is composed of a piezoelectric driving component and an elastic vibratory part, and the slider is composed of an elastic moving part and a friction coat.

Though there had been some earlier attempts, the practical ultrasonic motor was proposed firstly by Barth of IBM in 1973 [1]. A rotor was pressed against two horns placed at different locations. By exciting one of the horns, the rotor was driven in one direction, and by exciting the other horn, the rotation direction was reversed. Various mechanisms based on virtually the same principle were proposed by Lavrinenko [2] and Vasiliev [3] in the former USSR. Because of difficulty in maintaining a constant vibration amplitude with temperature rise, wear and tear, the motors were not of much practical use at that time.

In 1980's, with an increase of chip pattern density, the semi-conductor industry began to request much more precise and sophisticated positioners which do not generate magnetic field noise. This urgent request has accelerated the developments in ultrasonic motors. Another advantage of ultrasonic motors over the conventional electromagnetic motors with expensive copper coils, is the improved availability of piezoelectric ceramics at reasonable cost.

The merits and demerits of the ultrasonic motors are [4]:

Merits		
1.	Low speed and high torque	–Direct drive
2.	Quick response, wide velocity range, hard brake and no backlash	–Excellent controllability –Fine position resolution
3.	High power/weight ratio and high efficiency	
4.	Quiet drive	
5.	Compact size and light weight	
6.	Simple structure and easy production process	
7.	Negligible effect from external magnetic or radioactive fields, and also no generation of these fields Demerits	
8.	Necessity for a high frequency power supply	
9.	Less durability due to frictional drive	
10.	Drooping torque vs. speed characteristics	

Classification and Principles of Ultrasonic Motors

Two categories are being investigated for ultrasonic motors from a vibration characteristic viewpoint: a standing-wave type and traveling-wave type [4]. The standing wave is expressed by

$$u_s(x, t) = A \cos kx \cdot \cos \omega t, \tag{1}$$

while the traveling wave is expressed as

$$u_p(x, t) = A \cos(kx - \omega t). \tag{2}$$

Using a trigonometric relation, Eq. (2) can be transformed as

$$u_p(x, t) = A \cos kx \cdot \cos \omega t + A \cos(kx - \pi/2) \cdot \cos(\omega t - \pi/2). \tag{3}$$

This leads to an important result, i.e., a traveling wave can be generated by superimposing two standing waves whose phases differ by 90 degree to each other both in time and in space. This principle is necessary to generate a traveling wave on a limited volume/size substance, because only standing waves can be excited stably in a finite size.

The standing-wave type is sometimes referred to as a vibratory-coupler type or a "woodpecker" type, where a vibratory piece is connected to a piezoelectric driver and the tip portion generates flat-elliptical movement. The standing-wave type has, in general, high efficiency, but lack of control in both clockwise and counterclockwise directions is a problem. By comparison, the traveling-wave type (a surface-wave or "surfing" type) combines two standing waves with a 90° phase difference both in time and in space. A surface particle of the elastic body draws an elliptical locus due to the coupling of longitudinal and transverse waves. This type requires, in general, two vibration sources to generate one traveling wave, leading to low efficiency (not more than 50%), but it is controllable in both the rotational directions just by exchanging sine and cosine supplied voltages. Due to the necessity of the dual drive system, the traveling wave type is more complicated in structure and expensive in manufacturing cost than the standing wave type.

Conventional Motor Designs

Figure 2 shows the famous Sashida motor [5]. By means of the traveling elastic wave induced by a thin piezoelectric ring, a ring-type slider in contact with the "rippled" surface of the elastic body bonded onto the piezoelectric is driven in both directions by exchanging the sine and cosine voltage inputs. The PZT piezoelectric ring is divided into 16 positively and negatively poled regions and two asymmetric electrode gap regions so as to generate a 9th mode propagating wave at 44 kHz. A prototype was composed of a brass ring of 60 mm in outer diameter, 45 mm in inner diameter and 2.5 mm in thickness, bonded onto a PZT ceramic ring of 0.5 mm in thickness with divided electrodes on the back-side. The rotor was made of polymer coated with hard rubber or polyurethane.

Canon utilized the "surfing" motor for a camera automatic focusing mechanism, installing this ring-type motor compactly in the lens frame. Using basically the same principle, Seiko Instruments miniaturized the ultrasonic motor to a diameter as small as 10 mm [6]. A driving voltage of 3 V provides torque of 0.1 mN·m. Seiko installed this tiny motor into a wrist watch as a silent alarm. AlliedSignal developed ultrasonic motors similar to Shinsei's, which would be utilized as mechanical switches for launching missiles [7].

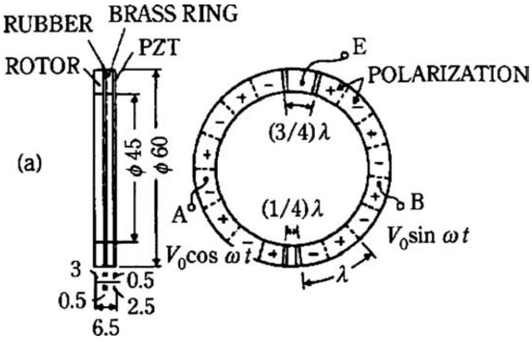


Fig. 2. Stator structure of Sashida's motor.

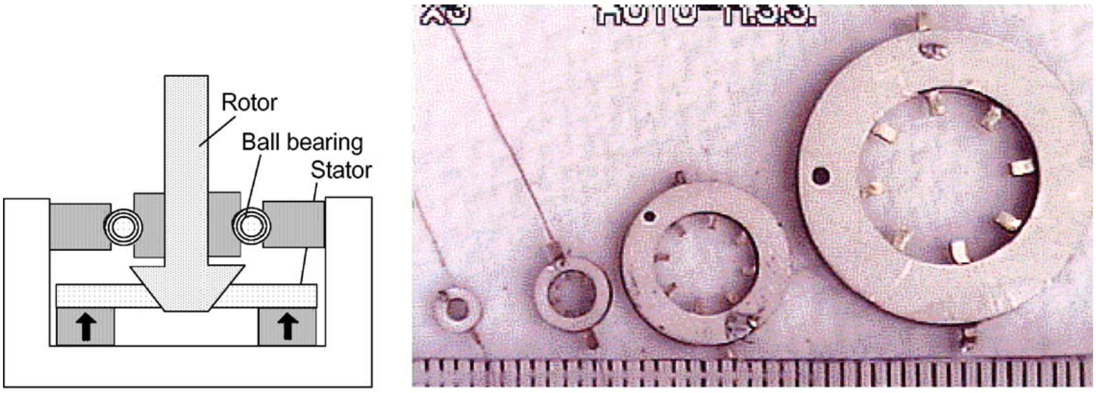
A significant problem in miniaturizing this sort of traveling wave motor can be found in the ceramic manufacturing process; without providing a sufficient buffer gap between the adjacent electrodes, the electrical poling process (upward and downward) easily initiates cracks on the electrode gap due to the residual stress concentration. This may restrict the further miniaturization of the traveling wave type motors. To the contrary, standing wave type motors, the structure of which is less complicated, are more suitable for miniaturization as we will discuss in the following. They require only one uniformly poled piezo-element, less electric lead wires and one power supply.

Another problem encountered in these traveling wave type motors is the support of the stator. In the case of a standing wave motor, the nodal points or lines are generally supported; this causes minimum effects on the resonance vibration. To the contrary, a traveling wave does not have such steady nodal points or lines. Thus, special considerations are necessary. In Fig. 2, the stator is basically fixed very gently along the axial direction through felt so as not to suppress the bending vibration.

We point out here also that one of the key factors for the actual commercialization of ultrasonic motors is to develop low loss and high mechanical quality factor piezoelectric materials, in order to suppress the heat generation during driving, which limits the continuous operation. We developed new ceramic series based on PZT-Pb(Mn,X)O_3 ($X = $ Sb, Nb) systems, which can be used for 10 times higher input/output power range than the commercially available *Hard* PZT's without generating significant heat. Refer to some recent papers [8, 9] on this issue.

Compact Motor Designs

We adopted the following concepts for developing new compact ultrasonic motors: (a) simplify the structure and reduce the number of component, (b) use simple (i.e., uniform) poling configuration; that is, "*Gentle to Ceramic*" and (c) use the standing-wave type to reduce the drive circuit components.



(a) (b)

Fig. 3. "Windmill" motor using a metal coupler with multiple inward arms. (a) Cross sectional view, and (b) photos of various size stators (3–20 mm ϕ).

Windmill Motor

We have developed a *Windmill* motor design with basically a flat and wide configuration, using a metal-ceramic composite structure [10, 11]. The motor is composed of four components: stator, rotor, ball-bearing and housing unit (Fig. 3(a)). The piezoelectric part has a simple structure of a ring electroded on its top and bottom surfaces (ϕ 3.0 mm) poled uniformly in the thickness direction. The metal ring machined by Electric Discharge Machining has four inward arms placed 90° apart on its inner circumference. The metal and piezoelectric rings are bonded together, but the arms remain free; they thus behave like cantilever beams (Fig. 3(b)). The length and cross-sectional area of each arm were selected such that the resonance frequency of the second bending mode of the arms is close to the resonance frequency of the radial mode of the stator. The rotor is placed at the center of the stator and rotates when an electric field is applied at a frequency between the radial and bending resonance modes. The truncated cone shape at the rotor end guarantees a permanent contact with the tips of the arms.

The operating principle of this motor is as follows: in the contraction cycle of the stator, the four arms at the center of the metal ring clamp the rotor and push it in the tangential direction. Since the radial mode frequency of the stator is close to the second bending mode frequency of the arms, the respective deformations are added and the tips of the arms bend down. In the expansion cycle, the arms release the rotor from a different path such that their tips describe an elliptical trajectory on the surface of the rotor. This motion seems to be a human finger's grasping-and-rotating action.

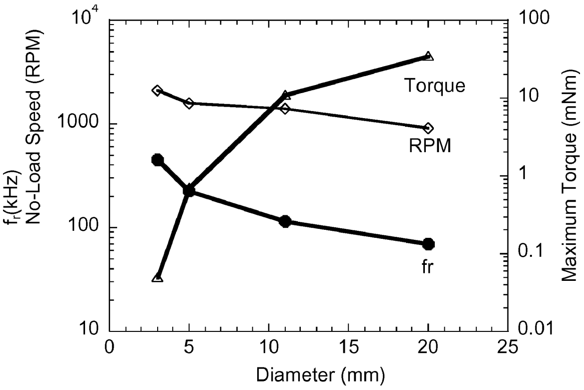


Fig. 4. Radial mode resonance frequency, no-load speed and starting torque vs. diameter of the stator, measured at 15.7 V.

Figure 4 shows the size dependence of the motor characteristics. When driven at 160 kHz, the maximum revolution 2000 rpm and the maximum torque 0.8 mNm were obtained for a 5 mm ϕ motor. Figure 5 shows motor characteristics in a 3 mm ϕ motor plotted as a function of load torque. A starting torque of 17 μNm is one order of magnitude higher than that of a thin film motor with a similar size [12].

PZT Tube Motor

In collaboration with Institute of Materials Research and Engineering, Singapore, we developed a PZT tube

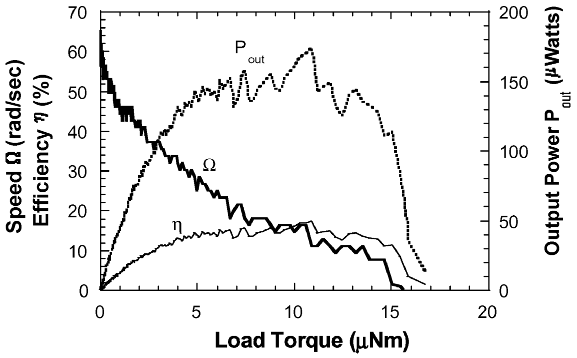


Fig. 5. Speed, efficiency, and output power versus load torque for a 3 mm ϕ motor.

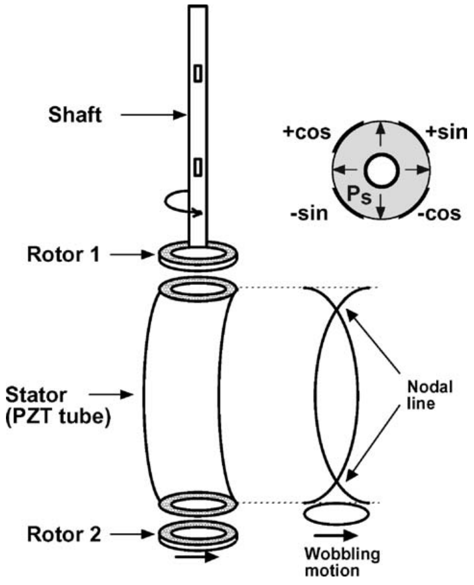


Fig. 6. Structure of a PZT tube type motor.

motor with a slim and long configuration [13]. The principle is similar to the one proposed by Tokin [14], which is schematically illustrated in Fig. 6. Four segmented electrodes were made on a PZT tube (1.5 mm or 2.2 mm in outer diameter) uniformly poled along the radial direction. A rotary bending vibration mode was excited on the PZT cylinder by combining sine and cosine voltages to the segmented electrodes, then two rotors were made to contact the wobbling tube ends for achieving rotation. The motion is analogous to a "dish-spinning" performance.

Our motor with 1.5/2.2 mm in diameter, 7 mm in length and 0.3 g in weight could generate 0.1 mN·m in torque and 1000–2000 rpm in no-load speed. Table 1 summarized the specification comparison with other commercialized motors. Our motors sustain the efficiency more than 20% in this size, which is one order of magnitude higher than the electromagnetic motors. Compared with Seiko motors, the PZT tube type exceeds more than 10 times in the power density (output mechanical energy/unit volume).

Although the motor characteristic is satisfactory for various applications such as intra-vascular medical micro surgery, there is one big problem, that is, difficulty in manufacturing fine and accurate PZT tubes, which leads to the expensive manufacturing cost.

Metal Tube Motor

In order to lower the manufacturing cost with keeping the motor performance, we have developed a metal tube type, as shown in Fig. 7(a) [15]. Instead of the

Table 1. Comparison of the motor specifications from Motorola, Seiko Instruments, and ICAT/Penn State.

	Motorola electromagnetic micromotor	Seiko ultrasonic micromotor	ICAT/PSU ultrasonic micromotor
Outer diameter (mm)	7	8	2.2
Length (mm)	16	4.5	8
Power source (V)	1.5	1.5* 3.5*	3–6*
(mA)	126	60 12	2–5
No-load speed (rpm)	5000	1200 1200	1000–2000
Starting torque (mN m)	0.075	0.05 0.1	0.1

*A booster circuit is required.

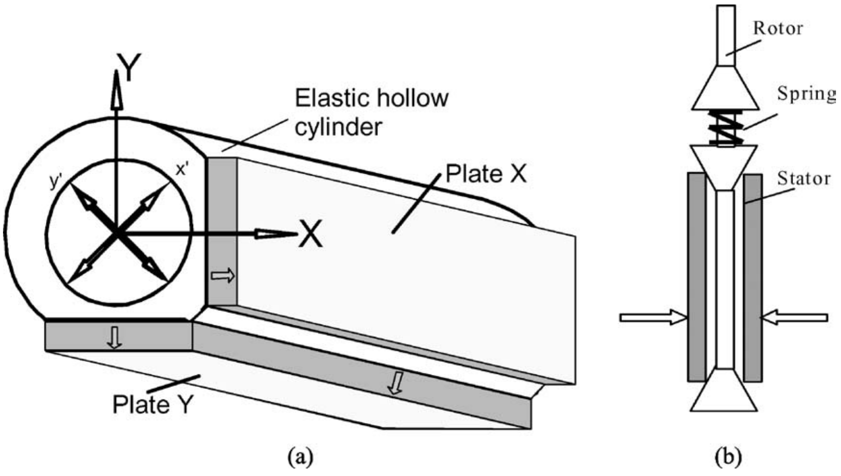


Fig. 7. (a) Structure of a metal tube stator, and (b) assembly of the motor.

PZT tube, we utilized a metal hollow cylinder, bonded with two PZT rectangular plates uniformly poled. Both can be easily found/prepared and cheap in price. When we drive one of the PZT plates, Plate X, a bending vibration is excited basically along x axis. However, because of an asymmetrical mass (Plate Y), another hybridized bending mode is excited with some phase lag along y axis, leading to an elliptical locus in a clockwise direction. On the other hand, when Plate Y is driven, counter-clockwise wobble motion is excited. Also note that only a single-phase power supply is required.

The rotor of this motor is a cylindrical rod with a pair of stainless ferrule pressed with a spring. The assembly is shown in Fig. 7(b). The power-related characteristics of a metal cylinder motor 2.4 mm in diameter and 12 mm in length with no load applied are plotted as a function of torque in Fig. 8. The motor was driven at 62.1 kHz in both rotation directions. A no-load speed of 1800 rpm and an output torque up to 1.8 mN·m were obtained for rotation in both directions under an applied rms voltage of 80 V. The very high level of torque produced by this motor is due to the dual stator configuration and the high contact force between the metal stator and rotors. The rather high maximum efficiency of about 28% for this relatively small motor is a noteworthy feature of the data presented in Fig. 8. One of the world's smallest ultrasonic motors to date is pictured in Fig. 9 [16]. It is 1.5 mm in diameter and 4 mm in length. The rotor is a thin hollow tube, through which an optical fiber can pass.

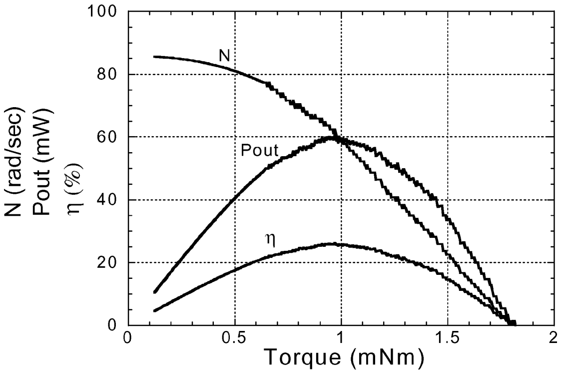


Fig. 8. The power-related characteristics of a metal cylinder rotary motor plotted as a function of torque, [Diameter: 2.4 mm, Length: 12 mm, Operating Frequency: 62.1 kHz, Load: none].

Shear-Type Motor

The above three motors were designed primarily aiming at discrete motor components, basically with using k_{31} mode. We describe here a new compact ultrasonic motor operated using the k_{15} shear-mode, of which the energy conversion rate from electrical to mechanical is much higher than the k_{31} type. Also this new design is compatible with the Silicon MEMS technology in the new future. Figure 10 shows a sketch of the new motor. The piezoelectric stator of this motor is constituted of a PZT ceramic disc with a center hole and a teeth type metal ring bounded to the disc. The piezoelectric disc was poled along its radial direction, the bottom electrode of which was divided into four parts with

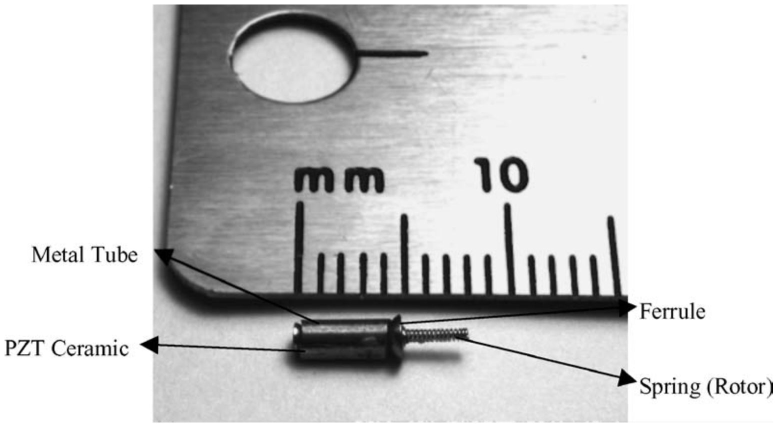
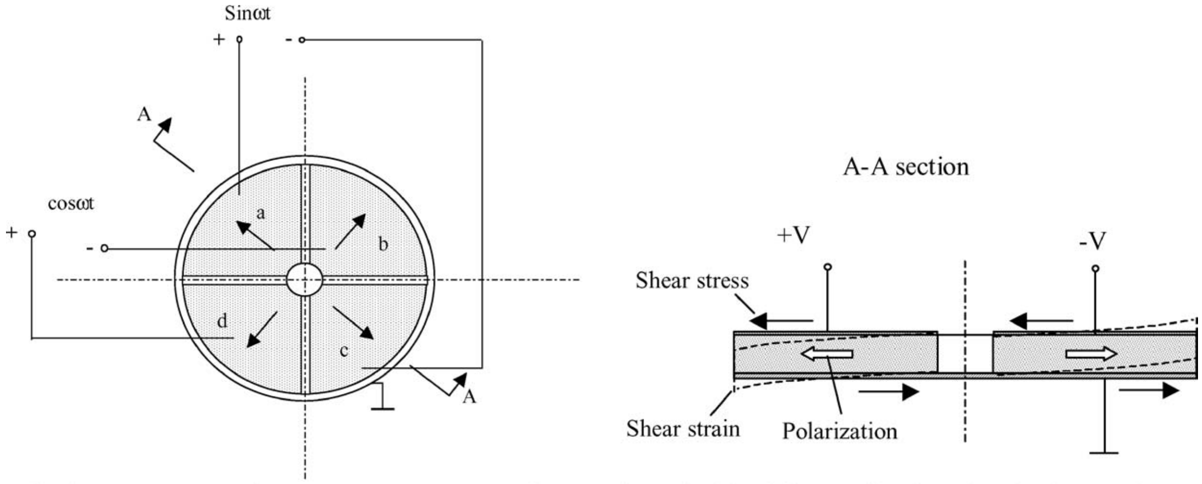


Fig. 9. One of the world's smallest ultrasonic motors to date [Diameter: 1.8 mm, Length: 4 mm].



(a) Shear motor stator element.

(b) Operation principle of flexure vibration using the shear-mode.

Fig. 10. Piezoelectric element for a shear-mode motor.

keeping the top electrode common. When a pair of voltage signals, sine and cosine, at the first shear-bending mode resonance frequency of the disc were input to the two pairs of electrodes, a traveling wave was generated circumferentially. Note that the shear mode excited in a finite size (diameter/thickness ratio $\ll$15) disk is inevitably associated with a bending mode. A ring with teeth was used to amplify the vibration level of the traveling wave, which drove a rotor in contact via mechanical friction. A prototype motor, whose stator was 10.5 mm in diameter and 2.2 mm in thickness with its first shear-bending mode resonance frequency at 38.9 kHz, exhibited the maximum no-load rotational speed of 200 rpm under 70 V_{rms}/8mA_{rms} applied.

Applications of Micro Motors

The ICAT at Penn State is conducting various micro motor projects at present, which are divided into three categories; (1) medical diagnostic and surgery devices, (2) office and IT equipment including laptop computers, printers, scanners and cell phones, and (3) micro machines. Figure 12 depicts examples for the medical catheter application, and Fig. 13 is a photo of the world smallest 4 WD vehicle with using a pair of the 4 mm long metal tube motors. Though the drive circuit and batteries have not been integrated at present, this tiny vehicle can be operated on a human finger by a joy-stick (Notice the finger print in the picture.)

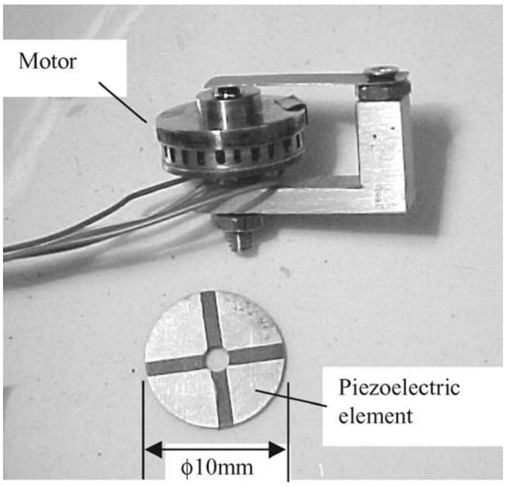


Fig. 11. Photo of the shear-mode motor.

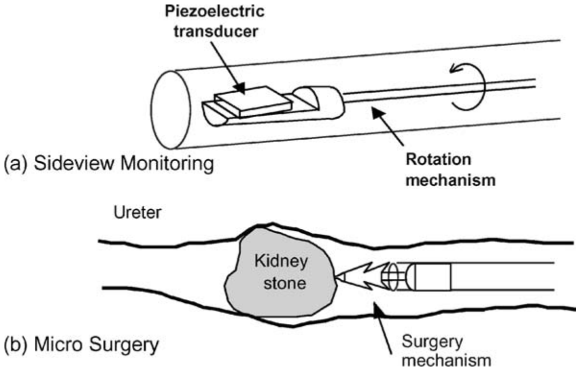


Fig. 12. Application examples of micro ultrasonic motors for the medical catheter application.

Summary

Ultrasonic motors are characterized by "low speed and high torque." Thus, the ultrasonic motors do not require gear mechanisms, leading to very quiet operation and space saving. Moreover, high power/weight ratio, high efficiency, compact size and light weight are very promising for the future micro actuators adopted to catheter or tele-surgery.

We introduced here three compact motors recently developed; flat type *Windmill*, thin & long *PZT tube* and its cheaper version, *metal tube*, and finally *shear* motor. For the further applications of the ultrasonic motors, systematic investigations on the following issues will be required: (1) low loss & high vibration velocity piezo-ceramics, (2) piezo-actuator component designs with high fracture resistance, (3) ultrasonic motor designs (standing-wave type, frictional contact), and (4) inexpensive and efficient high frequency/high power supplies.

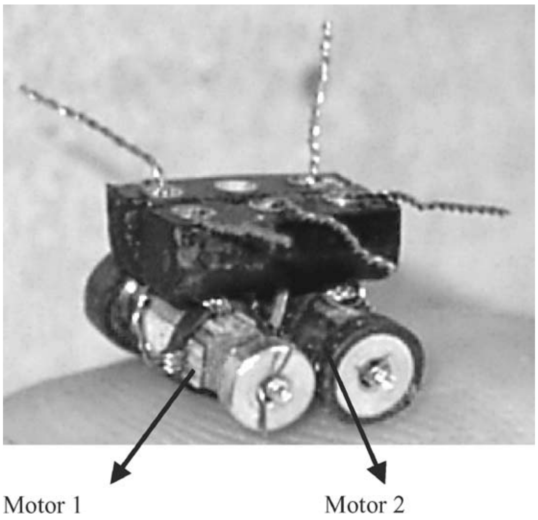


Fig. 13. World-smallest 4WD vehicle with using a pair of the 4 mm long metal tube motors. (Notice the finger print in the picture).

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