研究論文集 第33輯 2003年 12月 pp. 53~65

Actuating Characteristics of Electrostatic Micro-motors

Youngcheol Kim · Byungok Kim***

ABSTRACT

Electrostatic micro-motors can be divided into three classes: (i) salient type side drive motor, (ii) radial gap type wobble motor, (iii) axial gap type wobble motor. The working mechanism, torque evaluation, fabrication, and operational characteristics of each micro motors are compared. It is proved that axial gap type wobble motor has the bigger generating torque than that of the other type. The gear ratio of wobble motors increases the driving torque at the cost of a decreasing angular speed and decreases the friction because of the rolling motion instead of sliding at the bearing. Techniques for characterizing micro-motors performance are presented.

Key Words : Electrostatic Micro-motor, Wobble Motor, Salient Type, Radial Gap Type, Axial Gap Type

---

* Structural Department, Senior Researcher

** Structural Department, Researcher

1. Introduction

The mechanical design of micro-actuators can be divided into two classes: (i) mechanism and (ii) deformable microstructures. Mechanism type micro-actuators (e.g. micro-motors) provide displacement and force through rigid-body motion while deformable microstructures (e.g. comb drives) provide displacement and force through mechanical deformation or straining. The unrestrained, large motion capability of mechanism- type micro-actuators comes at the cost of friction, which is present in the bearings and joints of such devices. In contrast to the operation of macroscopic mechanical devices in which gravitational and inertial forces are often dominant, friction plays an important role in the operation of micromechanical devices. Deformable microstructures eliminate friction since they only utilize flexible joints and suspensions. However, avoiding friction comes at the cost of restrained (and often small) motion.

Micro-motor is a micro-mechanical device that produce large-motion for power linkages. Electrostatic micro-motors can be divided into three classes: (i) salient type side-drive motor, (ii) radial gap type wobble motor, (iii) axial gap type wobble motor. Because of large estimated driving torque, initial micro-motor design and fabrication attempts have been axial-gap architecture. However these designs suffered from instabilities in tilting and to a lesser extent in a vertical perturbations and fabrication complexity, that finally led to the development of radial-gap or side-drive micro-motors. Although the performance of these micro-motors is still emerging, they suffer from some drawbacks; driving torque and mechanical friction problems. Recently, the tilting, vertical, and radial instabilities of the axial-gap type wobble motors have improved largely.

In this paper, the working mechanism, torque evaluation, fabrication, and operational characteristics of each micro-motors are compared. It is proved that axial gap type wobble motor has the bigger generating torque than that of the other type. Finally, techniques for characterizing micro-motors performance are presented.

2. Working Mechanism of Micro-motors

2.1 Salient type Electrostatic Side-drive Motor

A SEM photograph of a salient type side-drive micro-motor is shown in the Fig. 1. Heavily-phosphorous-doped polysilicon is used for the rotor and the stator, and silicon nitride is used for electrical isolation.

Fig. 2 is a plane-view of the salient type side-drive motor in Fig.1 and describes the micro-motor operation. At the end of a phase excitation, the rotor is fully aligned with the excited stator phase (e.g., the configuration in Fig.2for alignment of rotor pole setwith stator phaseTo move the rotor clockwise, stator phaseis excited next. To move the rotor counterclockwise, stator phaseA would be excited next. Proper commutation of the excitation signal results in continuous rotation of the rotor. The operation of these micro-motors relies on the storage of electrical energy in a variable rotor-stator capacitance. The change in this capacitance in the direction of motion is proportional to the output torque of the micro-motor.

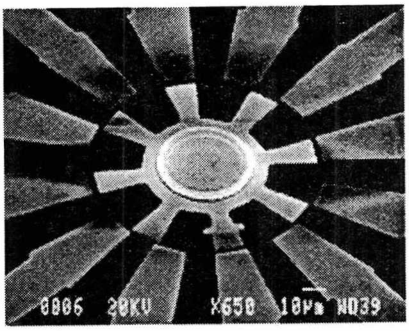


Fig. 1 SEM photograph of a salient type side-drive motor

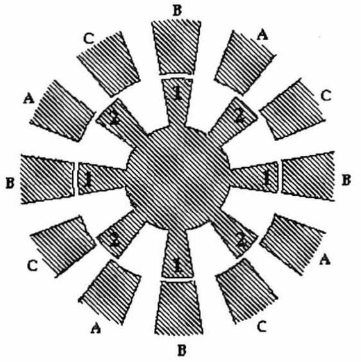


Fig. 2 Plane-view of a salient type side-drive motor

2.2 Radial Gap Type Elctrostatic Wobble Motor

A SEM photograph of a radial gap type wobble micro-motor is shown in the Fig. 3. The structural design of this wobble micro-motor is identical to that of the salient type, except that the rotor and stator designs are different. For the wobble micro-motor, the rotor has no poles (or no saliency). The central feature of the wobble micro-motor is that the rotor wobbles around the center bearing post as the excitation voltage is moved on the stator poles. Since there is a finite bearing clearance, the rotor's wobbling motion will also result in a rotation of the rotor.

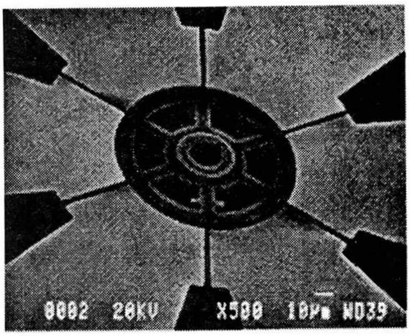
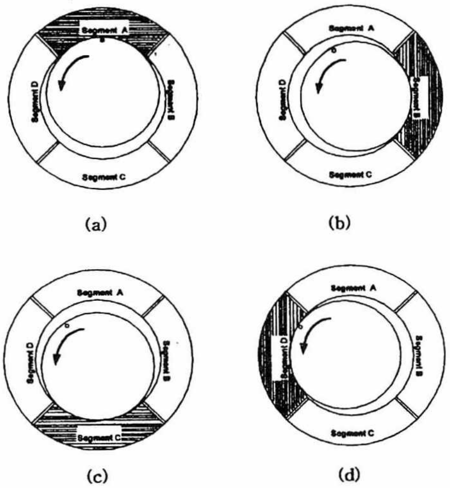


Fig. 3 SEM photograph of a radial gap type wobble motor



(a) (b)

(c) (d)

Fig. 4 Operating principle of a radial gap type wobble motor

The simplified structure and operating principle of wobble motor are Fig. 4. Initially a voltage is applied between the rotor and electrode A. This electrostatic force attracts the rotor toward electrode A as shown in Fig. 4(a). Next, a voltage is applied between the rotor and electrode B, causing the rotor to roll toward electrode B as shown in Fig. 4(b). Voltages are then applied sequentially to electrode C, D, and return to A. When the rotor has rolled around the stator once without slipping, the rotor has transversed a great distance than it's circumference. This difference in path length causes a differential rotation between the rotor and the stator.

2.3 Axial Gap Type Elctrostatic Wobble Motor

A SEM photograph of the salient type side-drive micro-motor is shown in the Fig. 5. This motor is sketched in Fig. 6. The rotor is resting, at the center, at a pin or ball bearing. When a potential difference between the rotor and one of the stator poles is applied, the rotor will be pulled down towards a contact point at the angular center of the excited stator pole. This results in an inclined position of the rotor.

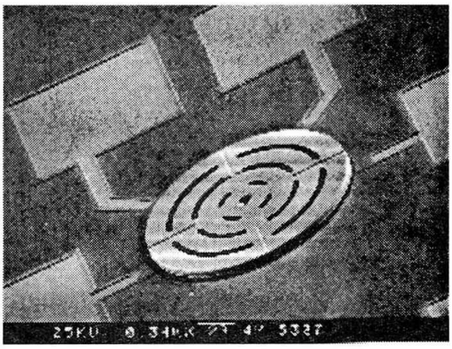


Fig. 5 SEM photograph of an Axial Gap Type Wobble Motor

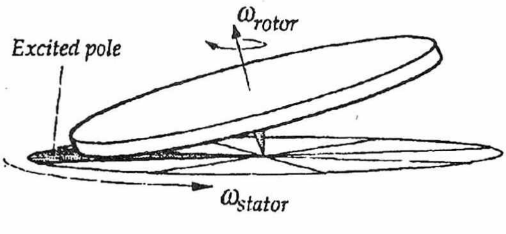


Fig. 6 Operational Principle of an Axial Gap Type Wobble Motor

Switching to other stator poles will movethis contact point around and the rotor is forced to roll at it's outer radius resulting in a rocking motion. Because of a difference in radius between the rotor and the resulting contact point circle, the rotor will be rotated by a small angle after one sequential activation of all stator poles.

3. Driving Torque Evaluation

3.1 Salient Type Elctrostatic Side-drive Motor

Two conducting parallel plates separated by an insulating layer create a capacitor with a capacitance given by eqn. (1).

$$C = \varepsilon_r \varepsilon_o w \frac{l}{d} \tag{1}$$

where w is the width of the plates, l is the length of the plates, d is the separation between the two plates and ε_o and ε_r are the free space and relative permittivities. If a voltage V is applied across these two plates, the potential energy of this capacitor is eqn. (2).

$$U = \frac{1}{2} C V^2 = \frac{\varepsilon_r \varepsilon_o w l V^2}{2d} \tag{2}$$

Taking the derivative with respect to x gives the force eqn. (3).

$$F_w = \frac{\partial U}{\partial x} = \frac{\varepsilon_r \varepsilon_o l V^2}{2d} \tag{3}$$

Fig. 7 shows the rotor (or stator) of an side-drive motor. The angular ring between r_i and r_o is filled with radial pole faces that are used to produce torque. The incremental torque produced by the incremental ring rdr is eqn. (4).

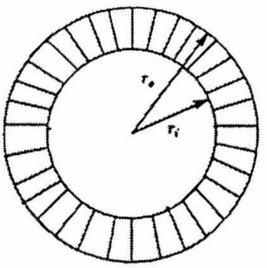


Fig. 7 The pole faces of the side-drive motor between radii r_i and r_o

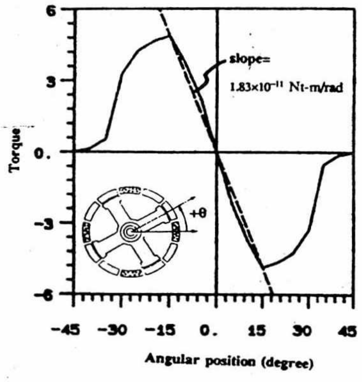


Fig. 8 A torque characteristic example of the salient side-drive motor

$$dT = r dF_w = \frac{r \varepsilon_r \varepsilon_o V^2}{2d} dl \tag{4}$$

The total length of the pole faces, dl, in this incremental ring is eqn. (5).

$$dl = \frac{dA}{np} = \frac{2\pi r dr}{np} \tag{5}$$

where dA is the area within the ring, p is the pitch of the pole faces, n is the number of motor phase, and dr is the width of the incremental ring. Integrating to obtain the torque,

$$T = \frac{\pi \varepsilon_r \varepsilon_o V^2}{3dnp}[r_o^3 - r_i^3] \tag{6}$$

Fig. 8 shows a torque calculation example of the salient side-drive motor.

3.2 Radial Gap Type Elctrostatic Wobble Motor

Radial gap type wobble motor has the electrodes which are insulated each other in the stator as shown in Fig. 4. Because the distance between electrodes is very small, if it is assumed to be ignored the distance incondition of analysis, wobble motor can be simplified as shown in Fig. 8.

First, the central shaft point P is (0,0). The central point of the stator and that of the rotor are (-δ,0) and (+δ,0) respectively. The physical length of air-gap, d is given by eqn. (7).

$$d = \sqrt{(x_s - x_r)^2 + (y_s - y_r)^2} \tag{7}$$

where,

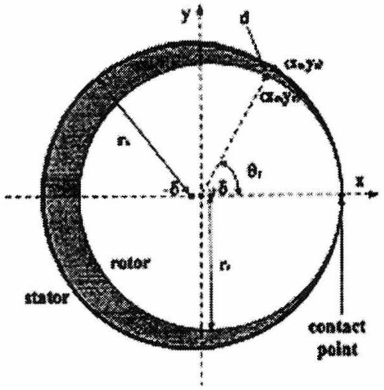


Fig. 9 Simplified radial gap wobble motor

$$x_s = \frac{-\delta \pm \sqrt{\delta^2 - \sec^2\theta(\delta^2 - r_s)^2}}{\sec^2\theta} \tag{8}$$

$$y_s = x_s \tan\theta \tag{9}$$

$$x_r = \frac{\delta \pm \sqrt{\delta^2 - \sec^2\theta(\delta^2 - r_r)^2}}{\sec^2\theta} \tag{10}$$

$$y_r = x_r \tan\theta \tag{11}$$

However, the physical length of this gap, d, between the rotorand stator is filled with an insulator of thickness t_r, and the rest is filled with air. If the relative permittivity of the insulator is ε_r, the length of effective air-gap, d_E, is given by eqn. (12).

$$d_E = d - t_r + \frac{t_r}{\varepsilon_r} \tag{12}$$

Also, the potential energy stored in the capacitor formed by rotor and electrode with the width w is obtained by eqn. (7).

$$U = \frac{1}{2}\frac{\varepsilon_o wl}{d_E}V^2 \tag{13}$$

where, ε_o is a dielectric constant in the free space, l is an axial length, and V is the applied voltage.

The torque produced by the motor is expressed by eqn. (14).

$$T = \frac{dU}{d\Phi} \tag{14}$$

where, the angle Φ is the rotation angle of the central shaft of the rotor. The angle θ is the variation angle from the axis x according to sequential excited electrode. One of the advantages of this motor is that the large ratio which can be obtained between θ and Φ. If r_r is the radius of a locus drawn by rotation of the rotor center and r_s is the radius of a locus drawn by rotation of the contact point, the gear ratio is given by eqn. (15).

$$\frac{\theta}{\Phi} = \frac{r_s}{r_s - r_r} \tag{15}$$

From eqn. (14), (15), the torque can be expressed as eqn. (16).

$$T = \frac{dU}{d\theta}\frac{r_s}{r_s - r_r} \tag{16}$$

And the stored energy of ncremental length along the electrode is given by eqn. (17).

$$dU = \frac{\varepsilon_o l V^2}{2d_E} r_s d\theta \tag{17}$$

The integral of the increments, $r_s d\theta$, from the starting angle of the electrode, θ_s to the ending angle of the electrode, θ_e gives the total energy, U is given by eqn. (18).

Table 1. Analysis model of a radial gap wobble motor

Radius of the stator		3.1852mm
Radius of the rotor		3.1648mm
The length of eccentricity		0.0127mm
Dielectric material of rotor	Thickness	0.0025mm
	Relative permittivity	3
Applied voltage of electrode		250V

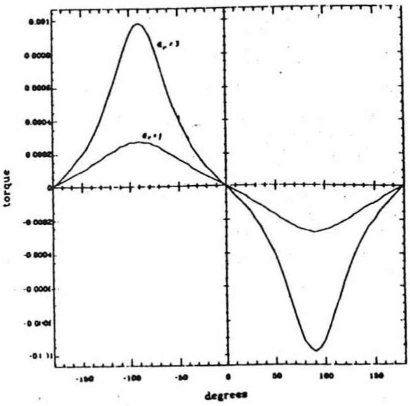


Fig. 10 Developed torque of a radial gap wobble motor

$$U = \int_{\theta_c}^{\theta_e} \frac{\varepsilon_o l V^2 r_s}{2d_E} d\theta \tag{18}$$

And if eqn. (16) is put into eqn. (18), developed torque of the angle θ is obtained by eqn. (19).

$$T = \frac{r_r}{r_s - r_r} \frac{\varepsilon_o l V^2 r_s}{2} \left(\left[\frac{1}{d_E} \right]_{\theta_e} - \left[\frac{1}{d_E} \right]_{\theta_s} \right) \tag{19}$$

By eqn. (19), the developed torque of wobble motor is changed according to gear ratio and a kind of dielectric material. Gear ratio can be changed by geometry of motor such as length of eccentricity of the stator and rotor. Developed torque obtained by eqn. (19) with design parameters of Table 1, is shown in Fig. 10.

3.3 Axial Gap Type Elctrostatic Wobble Motor

Fig. 11 is the schematic cross-sectional view of the rotor in axial gap wobble motor. Radius locus by contact point is eqn. (20).

$$R_c = \sqrt{R^2 + d^2} + (h_b - d)\sin\theta \tag{20}$$

where R is the rotor radius, d is the axial gap distance at the rotor center and h_b is the height of the bearing pin.

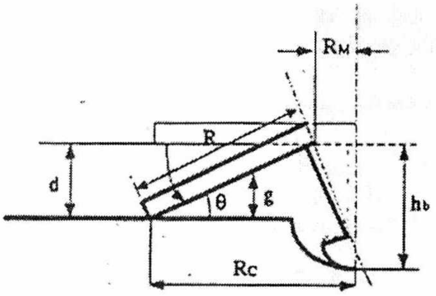


Fig. 11 Schematic cross-sectional view of the rotor

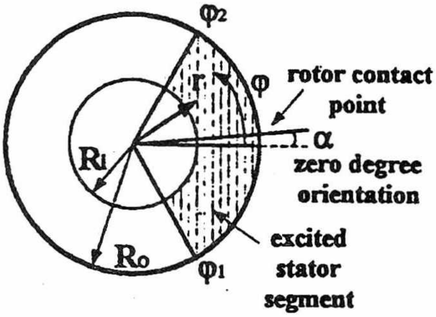


Fig. 12 Illustration of each parameters

For small rocking angle, the harmonic reduction ratio of the angular velocity between stator and rotor is given by the nominal gear ratio. From eqn. (20), the nominal gear ratio, n_o is eqn. (21).

$$n_o = \frac{R}{R - R_c} \approx -\frac{2R^2}{2dh_b - d^2} \tag{21}$$

The gear ratio is negative because the rotor rotates in a direction opposite to the exitation direction of the stator poles. When the bearing pin height is equal to d, eqn. (21)

reduces to $-2(R/d)$.

The tilt angle of the rotor is very small. Therefore the electrostatic field can be assumed to be vertical. Furthermore, fringing fields have been neglected and the rotor is assumed to be rigid. The axial gap between rotor and stator is eqn. (22).

$$g = [R - r\cos(\varphi - \alpha)]\sin\theta \approx d[1 - \frac{r}{R}\cos(\varphi - \alpha)] \tag{22}$$

where, α is the angle of the rotor contact point, φ is the angle of the stator pole from φ_1 to φ_2, and r is the radius of the stator pole from R_i to R_o.

Electrostatic energy of the excited stator segment integrated by dashed region in Fig. 12 is eqn.(23).

$$U = \frac{1}{2}CV^2 = \int_{\varphi_1}^{\varphi_2}\int_{R_i}^{R_o} \frac{\varepsilon_o r dr d\phi}{g + \frac{d_{ins}}{\varepsilon_r}} V^2 \tag{23}$$

where, d_{ins} is the thickness of the insulating layer with a relative dielectric constant ε_r between the rotor and the stator and V is the applied voltage between the rotor and the stator.

Developed single phase torque obtained by eqn. (23) with design parameters of Table 2, is shown in Fig. 13.

Table 2. Analysis model of an axial gap wobble motor

Rotor Radius	0.1mm
Axial-gap distance	0.002mm
Thickness of the dielectric layer	0.0002mm
Relative dielectric constant	7.5
Stator outer radius	0.1mm
Inner stator radius	0.05mm
Applied voltage	100V

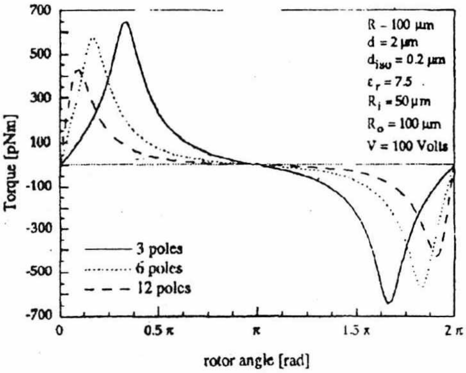


Fig. 13 Developed torque model of an axial gap wobble motor

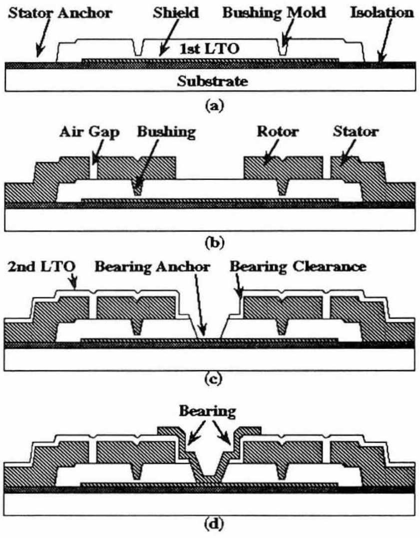


Fig. 14 Center pin bearing micro-motor

fabrication process

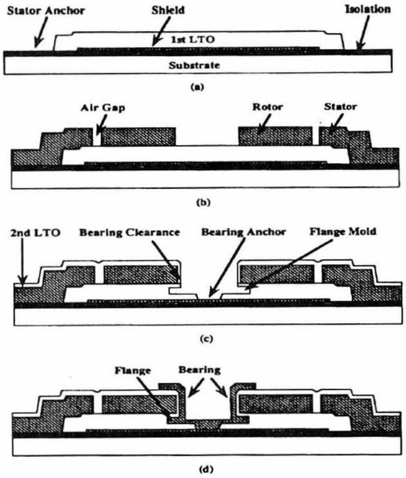


Fig. 15 Flage bearing micro-motor fabrication process

4. Fabrication

4.1 Elctrostatic Side-drive Motor

The most flexible polysilicon surface micromachining processes developed so far have been in conjunction with the development of micro-motors, which require the fabrication of bearings. Side-drive and wobble micro-motor require electrically conducting materials for the rotor and the stator, a requirement satisfied by heavily-phosphorus-doped polysilicon. The stator poles need to be electrically isolated from the rotor, the substrate, and one another. LPCVD silicon nitride can be used as an electrical insulator for this purpose. Fig. 14 and Fig. 15 show a fabrication process of the salient-pole and

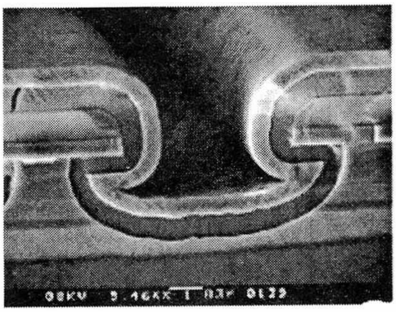


Fig. 16 SEM photograph cross section of a ball bearing like groove of axial gap type wobble motor

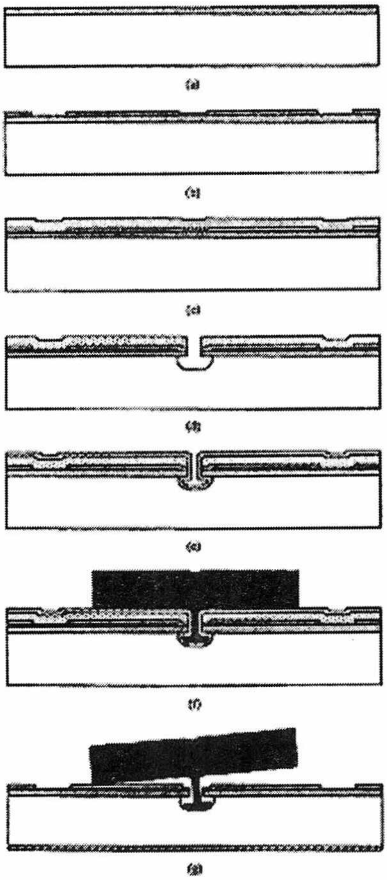


Fig. 17 Axial gap wobble micro-motor fabrication process

wobble micro-motors of Fig. 1 and 3. The center-pin and flange bearing micro-motor surface micromachining process requires three polysilicon depositions, two silicon dioxide depositions, and one silicon nitride deposition along with six photolithography (i.e., patterning) steps.

4.2 Elctrostatic Axial Gap Type wobble Motor

Axial gap type wobble motor is based on a four-mask process using polysilicon surface-micromachining techniques. Fig. 16 is SEM photograph cross section of a ball bearing like groove of axial gap type wobble motor. The fabrication sequence is shown in Fig. 17.

5. Performance Test

5.1 Test of Electrical Operation

Once the surface micromachining process has been completed and the structures released, device operation must be verified and evaluated. Because of the microscopic sizes of surface micromachined devices, device testing takes place on a probe station under an optical microscope.

The instrumentation needed for characterization of micro-motors consists of: (1)a probe station with at least seven micromanipulators; (2)a variable six phase power supply (preferably programmable) to provide required excitation signals to the stator poles; (3)oscilloscope to monitor the excitation signal; (4)a strobe with a variable delay triggering circuit for stroboscopic measurements; and (5)recording equipment. Fig. 18 shows a schematic of an experimental setup suitable for operating and characterizing micro-motors.

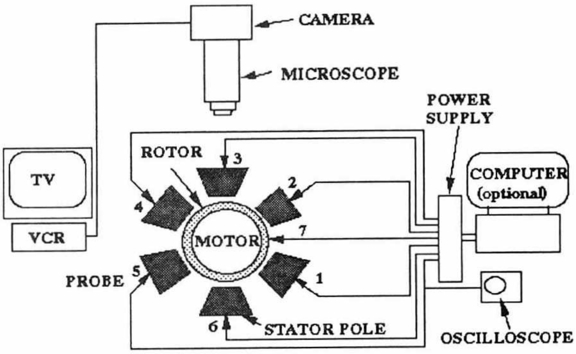


Fig. 18 Typical experimental setup for micro-motor test

For electrical operation, six probes are used forbiasing the stator poles, while the seventh is used to bias the rotor at ground potential as shown in Fig.18. Salient-pole micro-motors are tested using a three-phase bipolar (+/-V) square-wave excitation, while wobble motors are tested using a six-phase, unipolar (+V), square-wave excitation. The excitation voltages are typically between 30V and 100V, and the switching frequency of the square wave at one stator pole is in the range of 10-200

The simplest electrical test is to determine the minimum voltage required for sustaining motor operation (stopping voltage), as well as the minimum voltage required to restart (starting voltage) the motor. From measurements of the starting and stopping voltages, the starting and stopping torque can be determined using theoretical models of micro-motor operation. The starting and stopping torque data can be then used to determine frictional torques at the bearing and bushings (for a center-pin bearing process).

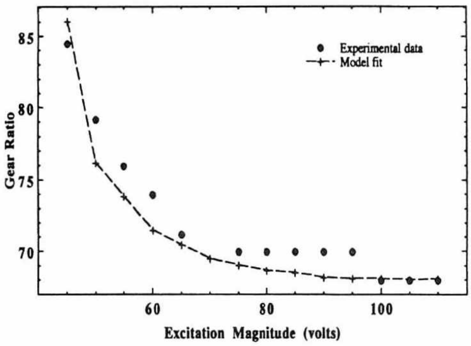


Fig. 19 Gear ratio versus excitation voltage magnitude for a typical wobble micro-motor

5.2 Gear Ratio and wear measurement

To characterize the operation of wobble micro-motors, the gear ratio of wobble micro-motors is measured as a function of applied voltage excitation. The gear ratio for wobble micro-motors is defined as the ratio of excitation frequency to the rotor rotational frequency, since the rotor rotates at lower speeds than the excitation frequency. Under ideal conditions, the gear ratio is a constant given by the ratio of bearing radius to the bearing clearance. Ideal conditions imply pure rolling of the rotor on the bearing during operation. However, in practice, the gear ratio of the wobble micro-motor is determined by a combination of rolling and sliding contact at the bearing surface. The sliding motion causes the rotor to slip, resulting in gear ratios larger than ideal gear ratio. The gear ratio is affected by the operating characteristics of the micro-motor, particularly the relative magnitudes of motive and frictional torque. The gear ratio is also affected by wear in the bearing which results in increased bearing clearance.Fig. 19 shows a typical gear ratio versus excitation voltage data.

6. Conclusion

The working mechanism, torque evaluation, fabrication, and operational characteristics of each micro motors are compared.(Table 3) It is proved that axial gap type wobble motor has the bigger generating torque than that of the other type. The gear ratio of wobble motors increases the driving torque at the cost of a decreasing angular speed and decreases the friction because of the rolling motion instead of sliding at the bearing.

Table 3 comparison of three type micro-motor

Type	Gear ratio	Torque	Bearing type
Salient type	Small	Small	Pin or flange
Radial gap type	Large	Medium	Pin or flange
Axial gap type	Large	Large	ball

References

1. S.F. Bart, M. Mehregany, L.S. Tavrow, J.H. Lang and S.D. Senturia, "Measurement of Electric micromotor dynamics," *Sensor and actuator., Vol. 19*, pp. 19-29, 1990.
2. M. Mehregany, S.D. Senturia, and J.H. Lang, "Measurement of wear in polysilicon micromotors," *Trans. Electron Dev., ED-39* , pp. 1136-1143, 1992.
3. R. Legtenberg, E. Berenschot, J. Baar, and M. Elwenspoek, "An Electrostatic Lower Stator Axial-Gap Polysilicon Wobble Motor Part II : Fabrication and Performance", *IEEE Micro Electro Mechanical Systems, Vol. 7, No. 1, March 1998.*
4. W. Trimmer and R. Jebens, "An Operational Harmonic Electrostatic Motor", Preceding *IEEE Micro Electro Mechanical Systems, pp13-16, February 1989.*
5. W. Trimmer and K. J. Gabriel, "Design Considerations for a Practical Electrostatic Micro-motor", *Sensors and Actuators, Vol. 11, pp.189-206, 1987.*