ME5656

Project Report

Friction Measurement and Lubricating of Rotary Silicon MEMS Device

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Abstract

MEMS (micro-electro-mechanical-systems) device has been a promising and fascinating topic in both mechanical and electrical engineering domains for decades with the revolutionary contributions to the contemporary micro-scale instruments especially for the micro-actuator and micro-sensor. Among the versatile material foundation to build up the MEMS device, silicon wafer is preferred to due to the semi-conductional electrical property and its chemical inertness. However, the surface tribological property of silicon wafer is not such admired as its other features aforesaid.

Rotary MEMS device based on silicon deserves broad applications since the requirements of rotary or oscillatory motions, such as micro-motor and rotary tribometer itself. This project report would take deep insights into the developments of rotary MEMS devices and their friction measurements. The mechanical governing equations which help the modeling and prediction of the device tribology behavior would be studied. Meanwhile, the corresponding simulation and fabrication would be also covered for the complementary understanding. Additionally, the asperity measurement technology for the rotary MEMS device would be discussed combined with the MEMS actuator. According to successful measurement of the surface asperity of the device, the optimal lubricating methods would be studied in order to reduce or avoid the wearing, fracture and even failure of the MEMS device.

Outline of the report

1. Introduction of the rotary silicon MEMS device tribology
   Understanding the micro-tribology in normal-scale existing theory
   Invalidation of micro-tribology by normal-scale existing theory
   Fundamental rotary MEMS device mechanical/structural modeling and equations
2. The harms due to the tribology in MEMS and different frictions and wearings
3. The asperity and related measurement technology for the rotary MEMS device — tribometer
   The principles of the tribometer
   Typical test configuration of tribometer
4. The strategies to lubricate the friction corresponding to the abovementioned rotary MEMS device
   Bio-inspired surface modification
   Micro-bearing
   Gas cushion lubricating
   Liquid cushion lubricating
   Other lubricating methods
5. Summary

1. Introduction of the rotary silicon MEMS device tribology

Most of the existing rotary MEMS actuators got their design inspirations from the counterpart of normal-scale device such as the turbine machine and motor. No matter what is the specific motivation to push such kind of research of micro-scale rotary device, the fundamental theories established for the normal scale devices such as different kinds of bearing could still advise the prediction, design and measurement of the MEMS scale counterparts. However, due to the fact of the large surface/ volume ratio of MEMS device and the micro-scale adhesion force, the tribology for the MEMS could be different from the regular size classic understanding even from its roots which lead to the special tribological results. And these special tribological results could be both on purpose of the design or application and harmful to its usage.

As above-mentioned, the regular size theory for engineering surface roughness and the surface contacting could still reserve their functions somewhat for the purposes of rough estimation and understanding the MEMS devices behavior. The general surface roughness statistic measurement such as CLA (central line average), skewness, and kurtosis could still help to evaluate the surface shape and height distribution just like we studied from the coursework (Eqs. 1). Additionally, other regular size surface contact theory still holds somewhat for the MEMS scale devices such as the Hertz contact model (Eqs.2) for MEMS bearing contact. So for the design objectives, the material selection and the geometry optimization could still follow the regular size classic theory for help. For example, the max allowable loading to the MEMS bearing system before the irreversible plastic yielding could also be estimated with Hertz contact model based analysis (Eqs. 3, Tresea).

$$R_a = CLA = \frac{1}{L}\int_0^L |z|\,dx \qquad Sk = \frac{1}{\sigma^3}\int_{-\infty}^{+\infty} z^3\Phi(z)dz \qquad K = \frac{1}{\sigma^4}\int_{-\infty}^{+\infty} z^4\Phi(z)dz$$

Eqs. (1)

$$a^2 = \frac{4WR}{L\pi}\left\{\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}\right\} \qquad \frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \qquad p_0 = \sqrt{\frac{E^*W}{RL\pi}}$$

Eqs. (2)

$$p_0^Y = 1.67Y \qquad p_m^Y = \frac{\pi}{4}p_0^Y = 1.3Y$$

Eqs. (3)

On the other hand, the MEMS device tribology owns its special issues which are usually neglected for regular size devices since these issues are only becoming dominant for large surface over volume ratio and special micro surface such as silicon wafer. Polycrystalline silicon is a kind of silicon material used popularly in MEMS industry due to its compatibility with IC (integrated circuit machining) and easy to be processed with low pressure CVD (chemical vapor deposition) and so on. For its benefits, lots of rotary MEMS devices could be fabricated by sacrificial film process to get hub-like rotary axle. However, silicon surface could become hydrophilic after its oxidation, which would make the device surface easy to adhere. Meanwhile, the oxidation of the silicon and other metal material used in MEMS could accumulate the static charge which leads the device surface to a dangerous situation.

The contact dynamic feature is also a concern for the MEMS actuator. The micro switches and micro relay and mirrors all require perfect dynamic response for contact according to the requirement of fast and nimble response. As for rotary MEMS device, the contact issue is usually solved with lubrication and optimal contact design. One more critical tribology topic is the concentrated strain (local max strain gradient) which could cause the curl of the thin film surface for MEMS.

In general, the MEMS tribology study could be performed on universal micro-laboratory to test its elasticity, stress response, adhesive and frictional properties as Fig. 1 (ref1). And the rotary MEMS owns its measurement facility and configuration due to the special property of spinning. So there is tribometer designed especially for rotary MEMS actuator as introduced later in Chapter 3.

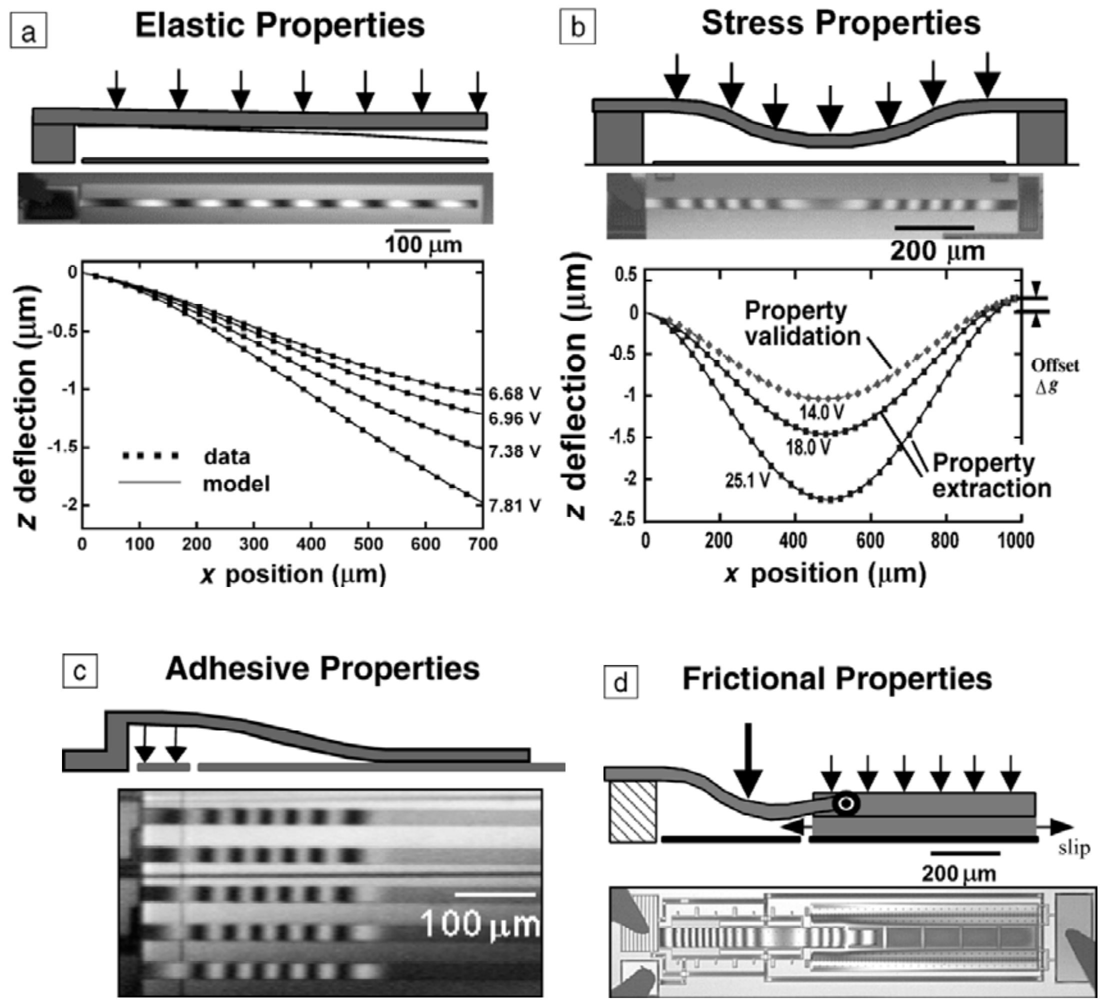


Fig. 1 micro laboratory on a chip for microtribology property [1]

Since most rotary MEMS actuators share the same style of micro-motor model, so the micro-motor was taken as a typical example in this report as Fig. 2 (ref. 2).

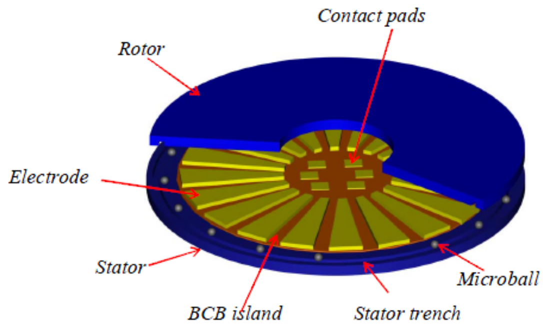


Fig. 2 geometry model of rotary micro-motor

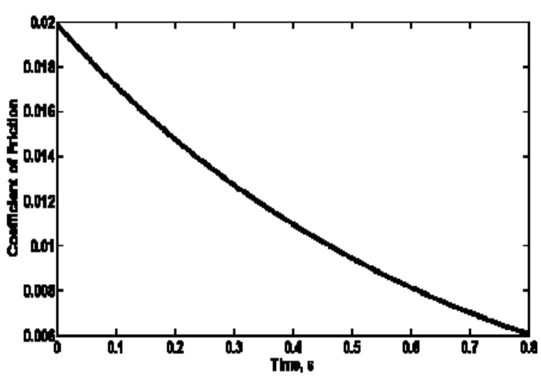
As Fig. 2 shows the rotor is supported by an array of micro-ball bearing mechanism. This model helps to understand the frictional forces and the impacts on them from operating velocities and normal loadings. The coefficient of friction, μ, is of interests. It is the ratio of the frictional to the normal force as the same with regular size definition. But the challenge is to extract the friction/torque data through experiment. Eq.4 describes the relationship of the friction torque and friction coefficient.

$$T_{Friction} = \mu MgR_0 \quad \text{Eq. (4)}$$

where M, R0, and g are the rotor mass, bearing radius, and gravity acceleration, respectively.

Also, the dashpot coefficient as B is defined as the ratio of the frictional force over the linear velocity of the rotor as Eq. 5.

$$F_{Friction} = Bv_{Linear} \quad \text{Eq. (5)}$$



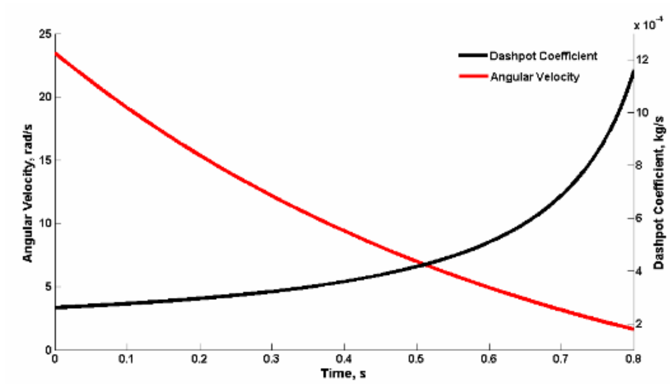


Fig. 3 (a) Measured coefficient of friction

Fig. 3 (b) Measured dashpot coefficient [2]

Fig. 3 presents the measured coefficient of friction and dashpot coefficient of micro-ball bearing supported MEMS rotary motor in [2]. The coefficient of friction could be got with spin-down test at 0 time origin and the dashpot coefficient increases with the decrease of the angular velocity of the rotor.

2. Harms, Frictions and Wearing

It is different from macro conditions, some forces (such as inertial force, electromagnetic force, frictional force and adhesive force) that will become the main forces to MEMS device. It is because the measurement of a structure changes from micro size to macro dimension. Because of the measurement decrease of MEMS device, the ratio of surface area to volume increases. According to the large surface to volume ratio, MEMS surface size effects emerge dramatically.

For example, when a model downsizes from 1 mm to 1 um, its area decreases 1 million times and the volume becomes 1 billion times smaller. Therefore, its inertial force, electromagnetic force, frictional force and adhesive force etc. which related to area of this model that is proportional to its volume increase several thousands of times and change into main forces of this model. Therefore surface effect influences micro systems much greater than macro systems. With the development of MEMS devices, as the separation of two contact structures are in the range of nanometer scale, even smaller, the frictional force affect between the two contact structures enhance significant. Because of the decreasing measurement of MEMS device, the frictional force between the two frictional structures influences the working behavior, mission life and dependability of developing MEMS devices greatly.

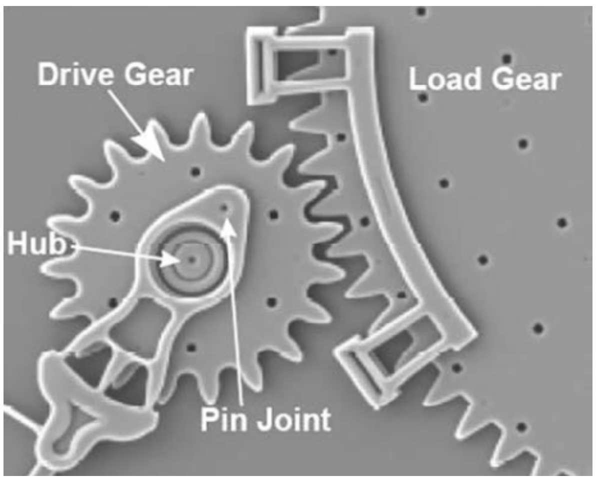


Fig. 4 SEM sketch of the micro-gear [10]

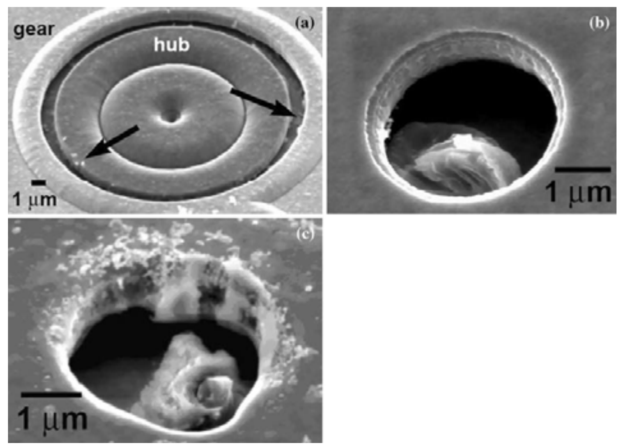


Fig. 5 SEM sketch of the gear hub and axis hole[10]

This system is damaged in short time. Absolutely gave us the real reason of the failure. They used SEM (scanning electron microscopy) to sketch out the whole process of the hub damaged (Fig. 5a) and found that wear chips were distributed everywhere. This demonstrated that there is seriously harm happened on the hub of this gear. They also contradistinguish the shape of the unharmed axis hole from the harmed axis hole (Fig. 5b and 5c). The SEM sketch draws the conclusion that the shape is totally deformed and there are a lot of wear chips. This demonstrated that the main reason of the harm of the micro devices is the micro-friction and it may absolutely short the operation life.

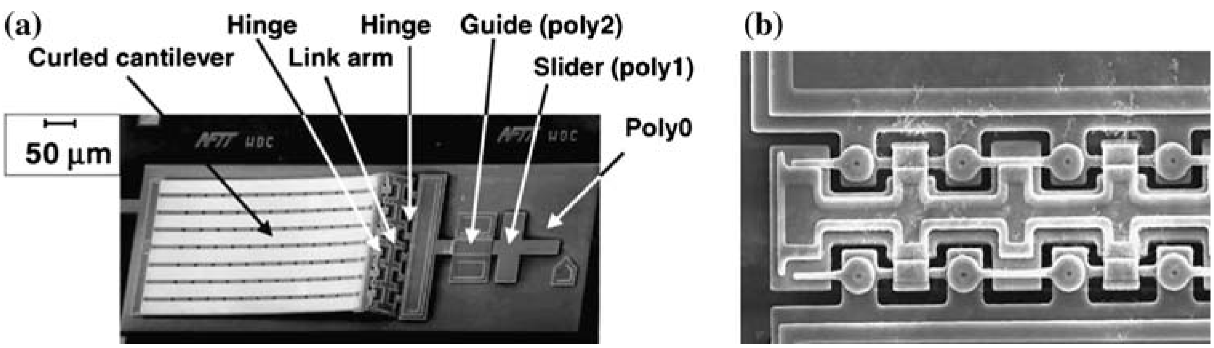


Fig. 6 MEMS electrostatic lateral output motor fabricated at Air Force Research Laboratory [10]

Fig. 6a is a MEMS electrostatic lateral output motor fabricated at Air Force Research Laboratory, the United States (Smallwood et al. 2006). This motor is also damaged and the reason is similar to the top example that is because the seriously micro-friction of the connecting hinge. (SEM also sketch of the harms on the hinge is shown as Fig. 6b) In order to avoid these harms, there is a very important point that must be cleared, tribology theory in nanometer scale range devices. Because the classical friction law could fail to predict and estimate MEMS devices. Therefore, it has to do research on micro-tribology extremely. Meanwhile, it is also very important to micro-tribology research finding a feasible experimental method that can make sure to obtain the credible data for the micro-tribology research.

Commonly, at the point of view of integration degree, there are two kinds of methods to measure the tribology characters of the developing MEMS devices. One kind is on-chip measuring method and the other is off-chip measuring method. Here lists the working principle of each kind and analyzes some testing results for each other as following.

3. Testing methods for micro-friction and tribometer

3.1 off-chip testing method for micro friction

This kind of test is performed between a MEMS surface and an external device. In contrast with on-chip testing, the procedure would be done out of the MEMS chip range. Usually, the MEMS surface is located fixed within the external tribometer. The clamp and fixture of the MEMS device could be the critical practical technologies. The practical applications belongs to this type include pin-on-disc testing, AFM and so on.

3.1.1 Micro-tribology test with the pin-on-disc measuring method

The alleged pin-on-disc measuring method is normally used in tribology tests. This device is based on a rotary platform test facility to place the samples, motor to drive the rotary platform test facility and the force testing system (Fig. 7a). An optical frictional force sensor is fabricated on the pin-on-disk tester to obtain the frictional force between the two frictional areas (Fig. 7b). It can sense the load and a fiberoptic system to obtain the deflection. In the test, one surface of the contact area is fixed on the rotary platform test facility while the other one is equipped on the test head (Fig. 7b). Normal force between the contact pairs can be defined by restoring force which is caused by the changing displacement result of the suspend beam in vertical direction. While frictional force can be defined by measuring the horizontal deformation of the suspended beam by the optical testing sensor.

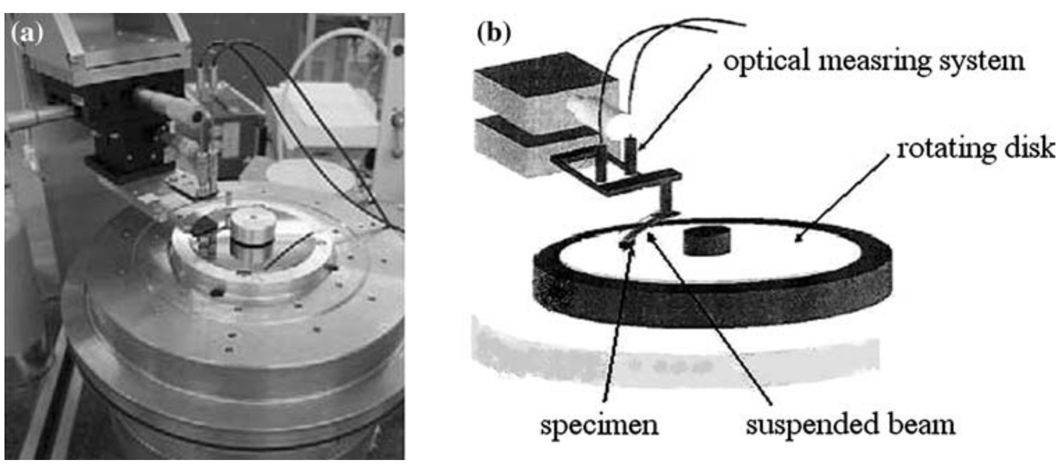


Fig. 7 Rotary platform test facility of the pin-on-disc measuring method [10]

(a Rotary platform test facility, b 3D stereogram of the testing system)

However there is a disadvantage in this testing system. Because it based on the measuring boundary of the force is in mN order, so it is hard to exactly make sure the frictional force of MEMS devices which the frictional force is in micro Newton order. Therefore this method is usefully to measure the tribology charactiers of the macro devices.

3.1.2 AFM

AFM technology uses the weak interaction (Van Der Waals Force) between its tip and the sample surface. The sample surface is fixed on the test flat platform, then the tip sweep along the sample surface. The core tip uses the V-shape cantilever structure which ensures it is sensitive to the surface micro force. The profile of the specimen surface is then got by the optical enlargement and measurement. AFM method has already been developed for decades as commercial method. But it still shows the drawbacks such as the limited capability for the large slope surface of the sample.

3.1.3 Private micro-tribology measuring method

The term for the method shows the special test configuration for the micro-friction property and profile. Private method is specific with different research institutes and it is always a optimal combination of the existing commercial methods.

3.2 on-chip method

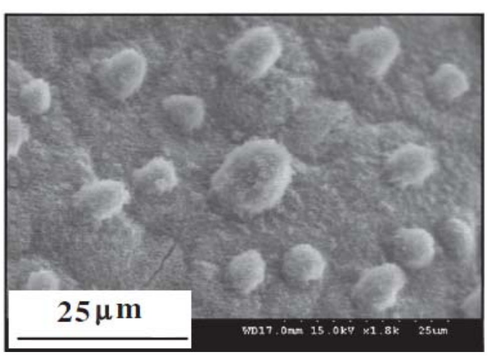
Since this test style requires all the performances carried out just on the MEMS chip itself, the application is relatively narrow and special. And it was introduced in the report at chapter1 (introduction) already.

4. The strategies to lubricate the friction of rotary MEMS device

4.1 Bio-inspired surface modification

For the tribology of MEMS, the benefits of the surface structure in the nature would inspire the researchers to treat the friction and wear of mobile MEMS device such as rotary actuators. One of the lasted bio-inspired studies for MEMS tribological property improvement was the imitation of the lotus leaf surface. The principle is the improvement of hydrophobicity which could reduce adhesion arising due to the capillary effects. And finally the friction could be reduced somewhat [3].

Fig. 8a [3] demonstrates the natural surface structure of lotus leaf and the bio-imitation surface treatment by SU-8 on silicon MEMS surface.



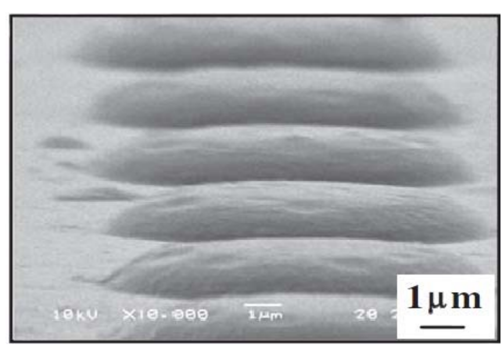


Fig. 8 (a) SEM image of the surface of a lotus leaf (b) SU-8 micro-patterns showing the shape of bumps [2]

Additionally, the friction coefficient traces for different surface patterns were recorded in [3] to verify the lotus leaf imitation benefits. The test was under 0.3N normal force and 15 mm/s relative motion speed. And the comparison is shown in Fig. 9. It could be observed that pure Si and Si/SU-8 plat surface are in good shape whereas the SU-8MP/)O2/PEFE, SU-8MP/Ar/PFPE and SU-8MP/PFPE surface treatments share the same trend and are closed to each other. Comparing with Si and Si/SU-8 surface, the frictions are already reduced dramatically. And the surface patterns were presented in Fig. 10. It could be got the good friction performance came from the effective lotus leaf-like surface micro-structure.

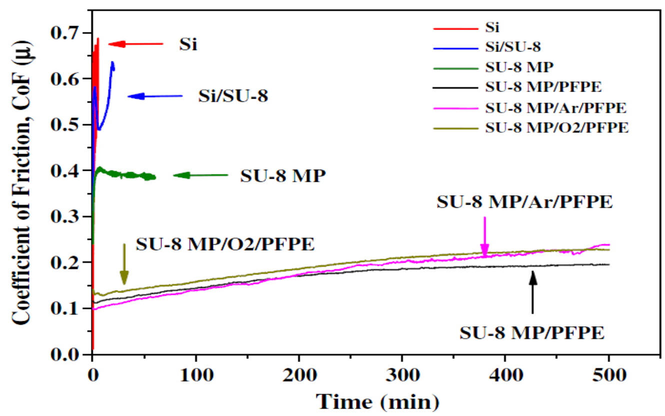


Fig. 9 Coefficient of friction (μ) as a function of time for different surface patterns [3]

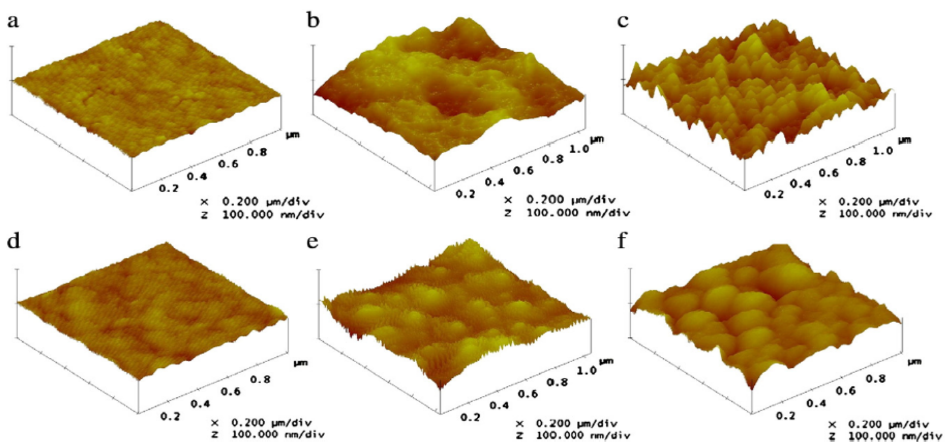


Fig. 10. AFM images taken on top of the micro-bumps of: [3]
(a) SU-8 MP, (b) SU-8 MP/Ar, (c) SU-8 MP/O2 and on those of their PFPE coated counterparts, namely (d) SU-8 MP/PFPE, (e) SU-8 MP/Ar/PFPE and (f) SU-8 MP/O2/PFPE. The scan area for all the images is ~1 μm×1 μm. The Z scale for all the images is 100 nm.

The fundamental equations to help understand such kind of bio-inspired friction treatment could be Eq. 6 and 7.

$$F_f = \tau A_r$$ Eq. (6)

$$A_r = \pi[\frac{R}{K}(F_n + 6\pi\gamma R + (12\pi\gamma R F_n + (6\pi\gamma R)^2)^{1/2})]^{2/3}$$ Eq. (7)

Where the τ is the shear strength, and Ar is real contact area. Eq. 7 is Johnson-Kendall-Roberts model which involves size of the tip R , the effective elastic modulus K, the applied normal load Fn and g, the interfacial energy of the material γ.

4.2 Micro-bearing strategy

Bearing has been a pretty conventional and effective component and strategy for the movable mechanical friction treatment. The advantage herein is the smooth transplant of the bearing theory and experience from the regular size bearing industry. However, the serious understanding of the modification due to micro-scale effects of MEMS should be carried out.

Among the rotary MEMS device bearing, the micro-ball bearing is accepted broadly. The reason for this popularity could be the benefits of rolling contact in MEMS which provides greater efficiency than planar contact bearing mechanisms. Meanwhile, it improves stability over levitated or fluid film bearings with mature fabrication programs.

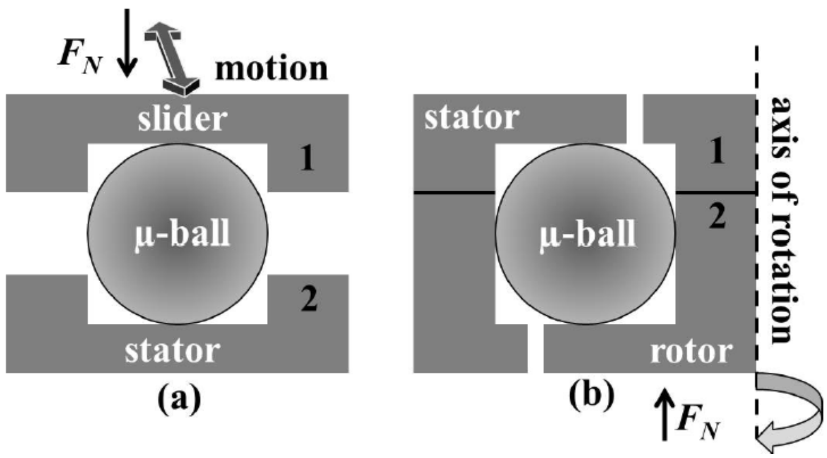
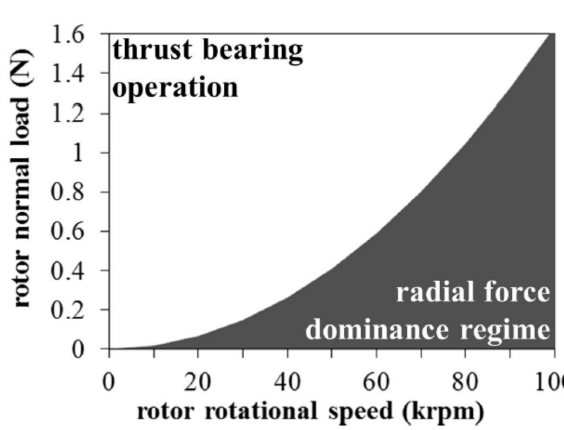


Fig. 11 2 typical micro-ball bearing structure [4]

Fig. 11 presents typical ball bearing structure of unbounded 2 silicon structure and unbounded silicon structures, respectively. They could be used for horizontal motion as (a) and rotation motion as (b). The design for micro-ball bearing for MEMS should include the considerations such as contact pressure and working speed. The Hertz contact model (Eqs. 2) still works here to help the estimation of the safe range of the contact pressure. Also, the material selection and the number of micro-balls to integrate for a bearing could be calculated. For example, as mN order rotor normal loads, the contact pressure beneath each micro-ball could be on order of MPa to GPa as [4] introduced. The other consideration is the working speed. The centripetal force acting on the rotating balls scales with square power of velocity, in this case, radial forces on micro-ball bearing would overcome the static coefficient of friction between the ball and raceway finally. Meanwhile, it would lead to the ball to ride against the sidewall.



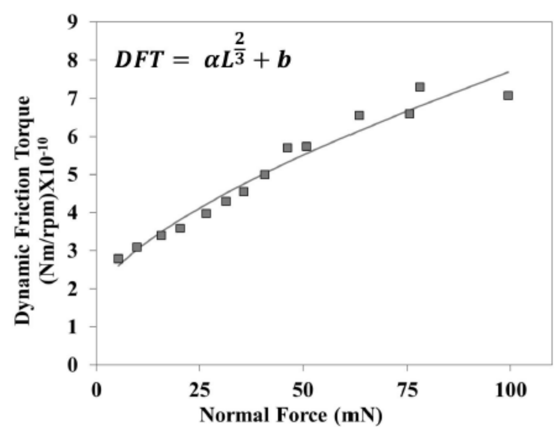


Fig. 12 Rotational speed effects on dominant operation regime [4]   Fig. 13 Dynamic friction torque [4]

Fig. 12 offers the general trend of the ball bearing operation dominance regime. For high spin speed, the force goes to radial stress when small rotor holding force is applied. In this case, the stability along the rotational axle would suffer. For the test of micro-ball bearing, spin-down test is a common choice to collect the dynamic friction torque with respect to normal force. MEMS rotary motor, pump and generator could use such kind of measurement to study its ball bearing property. And a curve fitting equation as Eq. 8 could be gained (Fig. 13).

$$DFT = \alpha L^{2/3} + b \qquad \text{Eq. (8)}$$

Where L is the normal load, b is load independent contributions to friction torque and α is constant dependent on materials and geometry.

4.3 Gas cushion lubricating

Besides the conventional mechanical rolling bearing, the fluid cushion strategy is also a possible method for the rotary MEMS lubrication. Of course, the gas lubrication owns the benefits as low mechanical noise, smooth, non-contact solid body and so on. On the other side, it also introduces the difficulty of the effective gas field design and the relying on gas source. However, as one development direction for MEMS lubrication, it is still worth discussing here.

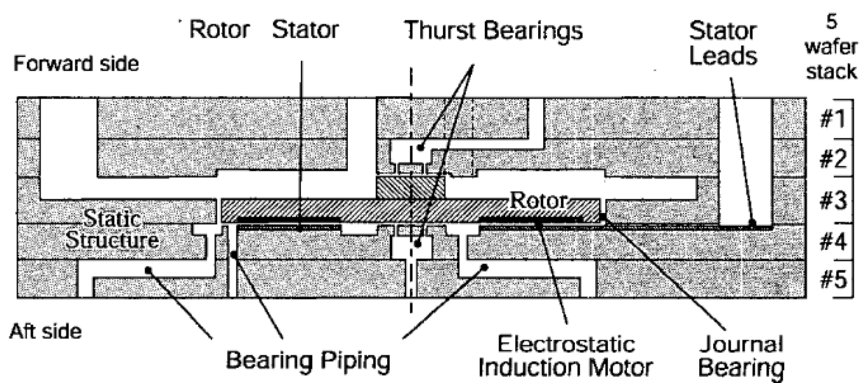


Fig. 14 Cross-section profile of gas lubrication MEMS motor [5]

Fig. 14 shows a structure of gas lubricated MEMS motor in [5]. Both thrust bearing and journal bearing were used within this MEMS motor. The thrust bearings were hydrostatic and certainly obey the thrust bearing property within the hydrostatic regime. And a balance could be got to float the rotor in the middle rotating without any axial solid contact. Then the journal bearing served the surrounding circular surface of the rotor with gas film to lubricate. For such kind of lubrication, the correct gas pressure and gas pipeline could be challenging.

Other fascinating research on gas-lubricated MEMS bearing consists of the theoretical modification to the regular size theory caused by the micro-size flow property. One example is the new model about the MEMS gas-lubricated journal bearing which concerns the slip flow effect [6] (Fig. 15).

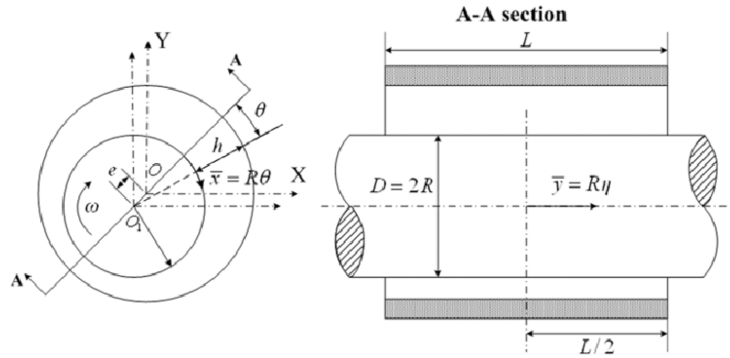


Fig. 15 micro-rotor supported by gas-lubricated journal bearing [6]

The mathematic deduction for the new model is complicated and due to the limited space for the report, only main roadmap was introduced here.

$$\tau = \frac{1}{2\pi} mn\bar{v}\frac{\partial u}{\partial z}\int_0^{2\pi}\int_0^{\pi/2}\cos^2\varphi\sin\varphi d\varphi d\beta = \frac{1}{3}mn\bar{v}\lambda\frac{\partial u}{\partial z} \quad \text{Eq. (9)}$$

Where τ is the momentum transfer rate for unit area by gas molecule. Other parameters are from the gas molecule [6].

The MEMS rotor always leads to the rarefied gas flow when it rotates. In this case, the Knudsen number is necessary to be calculated to find the slip velocity boundary conditions of the gas-lubricated journal bearing.

4.4 Liquid cushion lubricating

Liquid lubricating is similar to the gas counterpart at the point of view of the fluid dynamics, but it is different due to the liquid physical features such as viscous, imcompressible and large density in contrast with gas. Moreover, different from the regular size liquid lubricating, the MEMS counterpart presents the apparent surface tension performs relatively dominant to supply the bearing support force while the pressured liquid itself supplies the thrust as regular size bearing.

Since the clearance of the liquid between rotor and stator has the smaller order of the size of the liquid capillary effects, it is ensured the surface tension always works as main role for the liquid bearing. Meanwhile, according to the liquid property, the bearing wet area could be controlled in a local zone between the rotor and stator. The tiny liquid domain itself also functions to push the motor back to the initial center position within the irreversible range. The mechanisms for this design is shown in Fig. 16 [7].

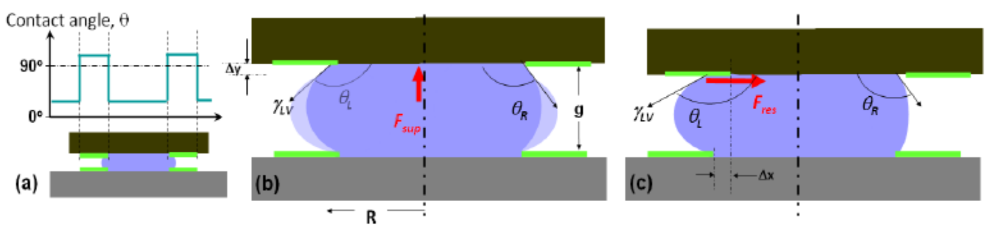


Fig. 16 [7] (a) contact angle along the surface; (b) the thrust; (c) the centering

The thrust force in Fig. 16 (b) could be modeled as Eq. 10 and the centering force shown in (c) from surface tension as Eq.11.

$$F_{thrust} = \frac{\pi R^2 \gamma_{LV}}{g}(\cos\theta_R + \cos\theta_L) + 2\pi R \gamma_{LV} \sin\theta_{R,L}$$ Eq. (10)

$$F_{centering} = 2(\gamma_{LV}\cos\theta_R - \gamma_{LV}\cos\theta_L)$$ Eq. (11)

Where, γ_{LV} is the fluid surface tension, g is the bearing thickness, R is the bearing radius, θ is the contact angle and the subscripts R and L denote right and left contact angle.
After the fundamental principle understood, the current research also found the shape of the liquid wetting zone affecting the bearing property. 3 typical shapes were tried to show the effects [7] as Table. 1.

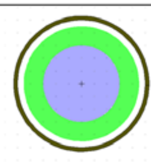
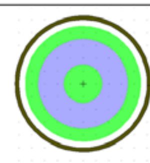
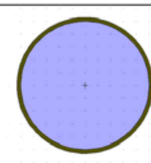
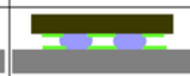
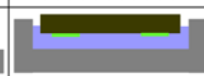
Bearing Design	Disk Bearing	Ring Bearing	Full Bearing
Top View of Bearing Liquid Cytop			
Cross Section View of Bearing			
Rotor Radius [mm]	5	5	5
Bearing Radius [mm]	3	Inner = 1.5, Outer = 3.5	5

Table. 1 Different liquid bearing geometries [7]

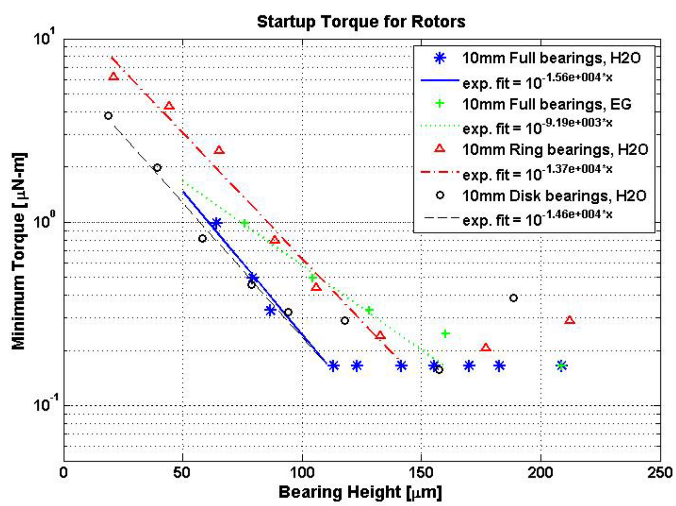


Fig. 17Start torque for motor with respect to varying bearing height and geometries [7]

The results of the measured start torque which is the minimum torque were summarized in Fig. 17. And it could be learned that the fluid viscosity is a minor factor for the low spin velocity. Also, which is pretty interesting, is the full bearing performs more stably in contrast with disk and ring bearing shape. If a magnet driven motor was tested with known start torque, the viscous drag coefficient b could be got as Eq. 12 (viscous friction model).

$$b = \frac{\mu\pi R^4}{2g}$$ Eq. (12)

For the rotary liquid MEMS bearing, the wobble is also under interests. The rotary axle stability is critical for its usage. One typical wobble record in 2D plane which is parallel to the stator surface was introduced by [7] as Fig. 18.

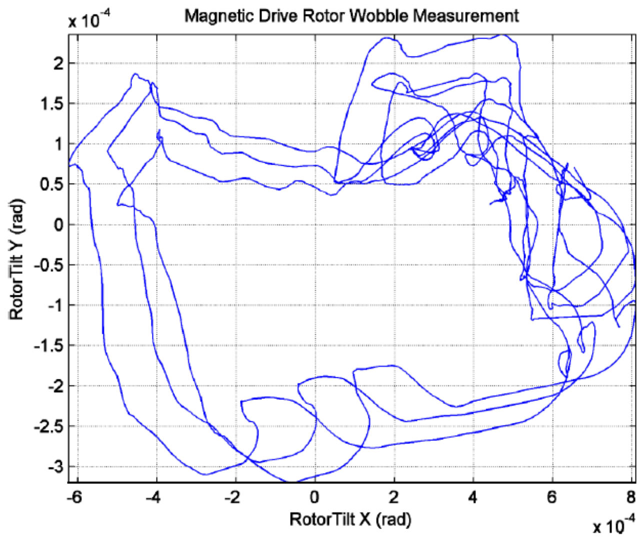


Fig. 18 Wobble trace of rotor axle of liquid MEMS bearing [7]
(full liquid bearing rotor spinning at speed of ~500 rpm)

4.5 Other lubricating methods

The main treatments and lubricating strategies were summarized as above-mentioned chapters. However, there are still other lubricating methods for rotary MEMS device.

One example as diamond-like carbon (DLC) nano-dot surfaces method is similar to lotus leaf bio-inspired strategy. As research done by [8] demonstrates that DLC has the potentially better tribological properties with the lower values of adhesion force and friction force in contrast with conventional silicon surface. And an experiment in [8] showed the functions of DLC surface (Fig. 19).

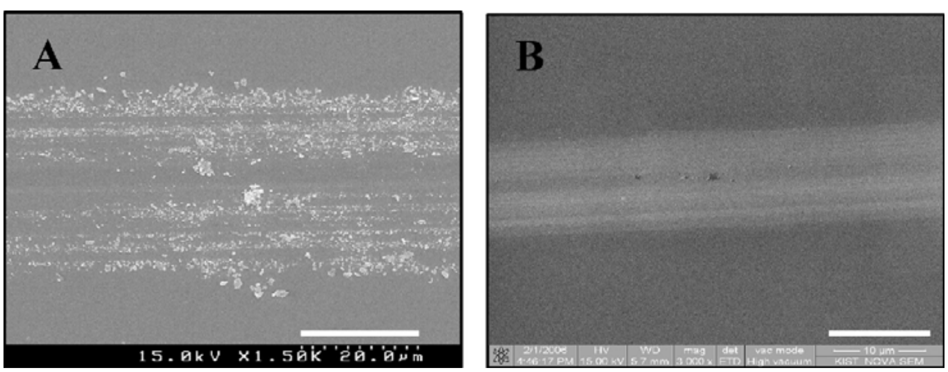


Fig. 19 SEM images of the worn surfaces: (A bare Si; B DLC surface) [8]

And the principles of this method could be explained by Eq. 6 and 7 just like the bio-inspried lotus leaf surface treatment.

One more example is the rotary MEMS friction depends on surface strucutral properties as bearing pad shape. The strategy origins from the regular size thrust bearing pad design theory. And this part of knowledge has been covered in our coursework. The amazing point is the feasibility of this design for the MEMS rotary device. A typical test was done with 3 different pad shape [9] as Fig. 20 and the friction coefficent test resutls as Fig. 21.

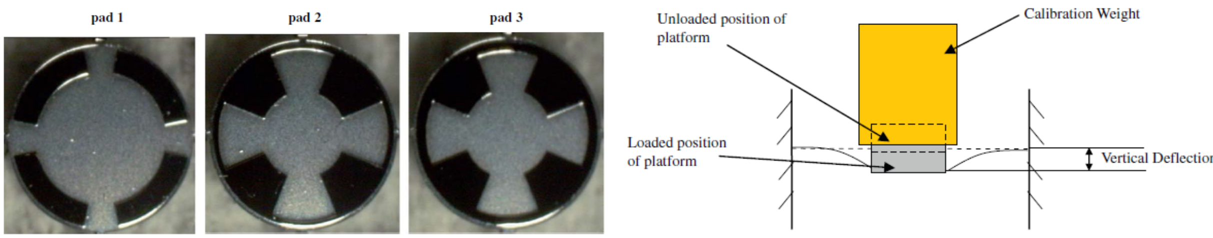


Fig. 20 (a) 3 different pad shapes (b) Test Configuartion [9]

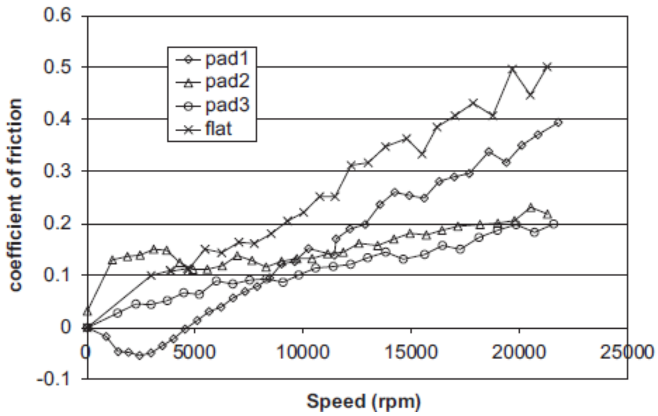


Fig. 21 Friction coefficent with differnet pad shapes [9]

Certainly, there still exist lots of attractive issues and topics for the tribolgy of rotary silicon MEMS device. The report has tired to browser and understanding the main trend under this topic and also explain with the theory just introduced in coursework. More open topics could be reviewed in the domain if no limits on the report length.

5. Summary

The report attempts to review the art of the tribolgy on the domain of rotary silicon MEMS devices. The fundamental mechanisms of the contact and friction and wear were studied with some theory from regular size and some specific propertes from the micro-scale due to large surface over volume ratio. The mathematical principles involved were tried to understood either with learned knowledge from coursework or from the reviewed literatures. The harms of the friction, wearing of MEMS devices were dicusssed together with the corresponding lubrication technologies to improve the tribological properties. It is found that some of the regular-size theories still helps for the MEMS scale while some other strategies like bio-inspried and speical micro-scale treatments needed for the lubrication.

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