Electrostatic micromotor and its reliability

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Abstract

Research and development in microelectromechanical systems (MEMS) have made remarkable progress since the advent of the first electrostatic micromotor in 1987. Considerable efforts have been directed to the investigation of the failure mechanisms and reliability of electrostatic micromotors. This paper provides a brief overview of failure modes and mechanisms and solving methods in electrostatic micromotors that are commonly met. It focuses on the introduction of the failure modes and mechanisms with numerical and experimental methods as well as the recent methods for reducing the failures and the development in future. In addition, the paper illustrates our investigation on the contact dynamics between the rotor and bearing hub and the effects of gas-lubricated bearing which decrease the possibility of friction, contact, and wear in electrostatic micromotors.

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1. Introduction

A microactuator is the key device for MEMS to perform physical functions. In microactuators, the popular actuation methods include electrostatic, magnetic, piezoelectric, thermal, shape memory, and other technologies [1,2]. Each actuation principle has its own advantages and disadvantages. The choice and optimization should be made according to the requirements of applications and one category of actuators is the micromotor [3,4]. At present, there are many kinds of micromotors, such as the electrostatic micromotor, ultrasonic micromotor, electromagnetic micromotor, resonant micromotor and biology micromotor.

Generally speaking, the electrostatic micromotors are suited for several lower torque, high-speed applications such as microsensors, microactuators, optical switches and data storage media [5]. Moreover, they are more suitable to perform tasks, which can be completed within a chip [6]. The successful electrostatic micromotors have been based on the various principle including corona, variable capacitance, harmonic drive, vibration, change induction etc. [7]. The electrostatic micromotors contain: top-drive motor, side-drive motor, wobble motor, center-pin motor, flange motor [8], linear stepper motor [9], ultrasonic motor [10], double stator axial-drive variable capacitance motor [11], out-rotor motor [12], induction motor [13], and shuttle motor [14]. In addition, there are many methods for the driving of electrostatic micromotors [15]. Table 1 lists the various electrostatic micromotors. Micromotors have not been widely used in industrial applications but are in a developmental stage, which suggests a near-future explosion of applications. For example, biomedical applications, drug delivery systems [16], surgical tools [17], probe [18], and resting in fluid for lubrication [19], are considered very

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promising. Micromotors can be used in optical systems in integrated circuits (ICs) for various purposes [20,21]. The application range of micromotors extends from systems for the maintenance of fine tubes in power plants to inspection of blood vessels in the human body. Ultrasonic intravascular systems are based on the use of catheters [16]. Isabelle Dufour et al. investigated the possibility of using an electrostatic micromotor for an intravascular echographic system. To overcome the drawback, putting a micromotor in the front of the endoscope to drive a triple prism seems to be an appropriate alternative [22].

Therefore, it is necessary to investigate the reliability of electrostatic micromotors in MEMS. The paper presents an analysis methodology to study the design for micromotor reliability, as shown in Fig. 1.

### 2. Failure modes and mechanisms

Reliability of micromotors is a very young and important field. A failure is said to occur when a micromotor or its system no longer performs the required functions under the special conditions within the stated period of time. There have two main failures: irreversible failures and degradation failures. Failure modes usually refer to observable effects and failure mechanisms, and there are the processes directly causing the observable failure modes. Table 2 shows the common micromotor failure modes and mechanisms.

<table>
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<tr>
<th>Failure modes</th>
<th>Failure mechanisms</th>
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<tr>
<td>Contamination</td>
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<td>Friction and Wear</td>
<td>Surface forces</td>
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<td>Stiction and Fracture</td>
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In MEMS, various forces associated with the device scale down with the size. When the length of a device reduces from 1 mm to 1 μm, the area decreases by a factor of million and the volume decreases by a factor of billion. The resistive forces like friction, viscous drag and surface tension that are proportional to the area, increase a thousand times more than the forces proportional to volume, such as inertial and electromagnetic forces. The increases in resistive forces lead to tribological concerns, which become critical because friction, wear and surface contamination affect device performance, and in some cases, can even prevent devices from working. Some of the important issues that affect the reliability of the micromotors are outlined below.
2.1. Friction

Friction forces have become the limiting factor to the successful operation and reliability of micromotors, which involve parts in relative motion to each other. There are two kinds of friction in micromotors [25]. One is caused by the weight of the rotor acting at the bushing, the other is due to the press against the hub. Tai et al. [26] presented a static frictional model to analyze the motion of a variable-capacitance IC-processed micromotor, and the frictional torque \( T_{\text{fric}}(\theta) \) consists of two components as

\[
T_{\text{fric}}(\theta) = T_0 + T_z(\theta) \tag{1}
\]

where \( T_0 \) is a constant frictional torque and \( T_z(\theta) \) a position-dependent frictional torque. The existence of the constant frictional torque \( T_0 \) is expected to exist at the surfaces of the rotor and hub.

Bart et al. [27] yielded a new dynamic model, which included the dynamical friction and helped to understand either or both of the voltage dependent friction mechanisms. The formulation is

\[
J\ddot{\theta} = -B\dot{\theta} - \left( C_{sp} + C_b \frac{R_b}{A_b} \right) V^2 \cdot \text{sgn}(\dot{\theta}) + AV^2\gamma(\theta) \tag{2}
\]

where \( J \) is the rotor moment of inertia, \( B \) is a coefficient of viscous drag, \( \dot{\theta} \) and \( \ddot{\theta} \) are the angular velocity and acceleration respectively, \( A \) is the amplitude normalized to the square of the drive voltage \( V^2 \), \( A_b \) is the bushing area, the coefficient \( C_{sp} \) represents the friction contribution due to lateral forces and \( C_b \) denotes the contribution attributed to rotor-to-ground-plane forces, \( \gamma(\theta) \) represents the shape of the drive torque as a function of the rotor position.

Most of the friction forces resisting motion in the micromotor are concentrated near the rotor and hub interface where continuous physical contact occurs. Surface roughness of the surfaces usually has a strong influence on the friction characteristics on the micro-scale. It is therefore critical to determine the friction forces present in micromotors. Table 3 displays static friction coefficients of various electrostatic micromotors. Tai et al. [26] measured in situ the starting torque and pausing position for different starting positions under a

<table>
<thead>
<tr>
<th>Reference</th>
<th>Device</th>
<th>Method</th>
<th>Materials</th>
<th>Friction coefficient</th>
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</thead>
<tbody>
<tr>
<td>Tai et al. (1990) [26,62]</td>
<td>IC-processed micromotor</td>
<td>In situ kinetic friction starting voltage</td>
<td>PolySilicon/Si3N4</td>
<td>0.18–0.38</td>
</tr>
<tr>
<td>Dhuler et al. [28]</td>
<td>Wobble micromotor</td>
<td>Dynamic model with experiment data</td>
<td>PolySilicon/PolySilicon</td>
<td>0.38–0.55</td>
</tr>
<tr>
<td>Matheison et al. (1996) [29]</td>
<td>LIGA micromotors</td>
<td>Cantilever/fiber deflection rig</td>
<td>Ni/Alumina</td>
<td>0.60–1.20</td>
</tr>
<tr>
<td>Tas et al. (1997) [24]</td>
<td>Linear stepper micromotor</td>
<td>Friction meter</td>
<td>PolySilicon/SiO2</td>
<td>0.50–1.10</td>
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constant-bias voltage to obtain the static friction of a rotor and bearing interface in a micromotor. A friction–torque model was used to obtain the coefficient of static friction. Mathieson et al. [29] developed a cantilever deflection rig to measure friction of LIGA-processed micromotors. Most of these techniques employ indirect methods to determine the friction forces of micromotors.

2.2. Wear

In a micromotor, the rotor is driven electrostatically in the stator. However, in practice, there may be some physical contact due to the small clearance between the rotor and hub. Adhesive wear and abrasive wear often occur between the rotor and ground plane. Research at ATT Bell Laboratories has provided the first information on mechanical wear in micromotors. The polysilicon rotor has been driven by air pressure at 2500 rps and the hub has clearly been eroded and misshapen severely at this high speed [30].

Wear limits the lifetime and constrains the performance and reliability of micromotor. The intermittent contact at the rotor–stator interface and physical contact at the hub flange interface result in wear issues (shown in Fig. 2). One solution is to replace the sliding contact at the center with rolling contact. A rotor is a smooth ring and, by electrostatic attraction, rotates eccentrically without slipping at the contact with shaft. Another way to avoid the effects of friction is with elastic supports [6].

In addition, the roughness on the rotor inner radius side wall gives rise to significant initial wear in the micromotor bearing as the side wall asperities wear out [23,31]. The polysilicon shield surface is characteristically rough on the micro-scale but the bushing surface sliding on the shield is comparatively smooth. The roughness of the shield surface reduces the real area of contact between the bushing and the shield significantly and the real area of contact is comparatively small in all cases. The roughness of the rougher surfaces in polysilicon micromotors is of the order of 60 nm [23,31].

2.3. Stiction

Stiction can be prevented or reduced in several ways which can roughly be divided into two groups: methods based upon the prevention of physical contact between structures and the substrate during fabrication; methods based upon the reduction of adhesion forces.

Stiction is a well-known and almost unavoidable problem that occurs in micromotors fabricated by surface micromachining. In addition to friction and wear, stiction occurs when surface adhesion forces are higher than the mechanical restoring forces of the micromotors. And stiction between the contact surfaces limits the repeatability of operation or may even prevent the operation completely. The components of the micromotor are small, therefore, the surface forces can dominate each other and cause these parts come into contact. The most key forces in micromotor are the electrostatic force, capillary forces, Van der Waals forces, Casimir forces [32]. The surface roughness is a major influence in the stiction phenomenon [33]. In addition, more quantitative modeling of the effect of surfaces roughness on stiction was performed, resulting in the van Spengen stiction model [68,69]. In this model, the statistical distribution of the distance of the rotor and substrate rough surfaces with respect to each other is used to calculate the surface interaction energy (Fig. 3). The surface interaction energy can be calculated by

\[ E_i = \int_0^\infty \frac{c_i}{z^{m_i}} h(z) \, dz \]  

where \( E_i \) is the surface interaction energy due to mechanism \( i \), \( \frac{c_i}{z^{m_i}} \) is the dependency of the amplitude of the surface interaction energy on the distance \( z \), and \( h(z) \) is the distribution of the distance between the rough surfaces.

2.4. Fracture

Fracture strength, a statistical property in brittle materials such as silicon, is a function of microstructure and processing, which can exhibit variability from run to run due to process variability. Stress in polysilicon
elements should be kept to 10% or less of the measured fracture strength for the material and process in use. Stress values in the range of several hundred MPa appear to be quite acceptable.

Fracture occurs when the applied load on a micromotor is greater than the strength of the component materials. Fracture is a serious reliability concern because it can immediately cause catastrophic failures, particularly for the brittle materials. Therefore, it is very important to know the mechanical properties of the materials under micro-scale for micromotors.

2.5. Contamination

Atmosphere, humidity and temperature play an important role in the tribological behaviors of micromotors. The effect of the environment depends on the design of the bearings. A small increase in the normal contact force was increased in room air as compared to nitrogen due to the increase of the coefficient of friction [8]. Dust particles attracted electrostatically from the air or generated during rotor and hub grinding caused the abrupt jamming of the rotor [26].

2.6. Electrostatic interference

Materials of extremely high insulation resistance and breakdown field strength, such as silicon oxide and silicon nitride, are often used for insulation in MEMS devices and as part of electrostatic micromotors. The surface of such dielectrics can be charged up locally and the charge retained for a considerable time under certain conditions. Sometimes they provide trap sites for positive and negative charges both deep in the volume and at the interfaces in multilayer stacks. Electrostatic charging effects are of great importance to micromotors as they can be a significant fraction of the total normal force applied to a mechanical contact.

During motor operation, the rotor is tended to be in electrical contact with the ground plane (substrate), or shield, beneath it by the bushing or the hub. A part of the rotor structure of an electrostatic micromotor as shown in Fig. 4. This electrical contact insures that the rotor and the shield are at the same electric potentials, therefore, eliminating the clamping forces otherwise cause by the electric field between them. As reported in [34], new oxide formation on the polysilicon surfaces can prevent motor operation by disrupting the intended electrical contact.

2.7. Tribological problem

Furthermore, tribological problem is another important factor affecting the performance and reliability of micromotors. To guarantee the function and reliability of MEMS devices, tribologists must understand the origins of adhesion, friction, and wear over a broad range of length scales from the macroscopic to the microscopic. It is necessary to develop a fundamental understanding of friction, wear phenomena on the scale pertinent to MEMS and understand the surface contamination and environment in micromotors. Another requirement is to develop lubricants and identify lubrication methods that are suitable for micromotors. The tribological issues during micromotor operation are shown in Fig. 5.

3. Studying the failure mechanisms

Experimental and numerical methods can be used to study the friction and wear issues in micromotors.

3.1. Numerical methods

Simulation is of vital importance in engineering applications and its power can be brought to bear on micromotors. Quick, low cost, easy and optimum solutions for practical engineering applications and research can be obtained by numerical modeling using finite element, finite volume and boundary element methods. VHDL-AMS have been used for micromotors system modeling, Spice and Saber for electrostatic, ANSYS for multidomain (mechanic, thermal and electrostatic)
simulations. Specialized CAD tools, the mTORQUE and MICROTOR are two PC-based design tools devoted to the design and simulation of static and dynamic behavior of various constructions of integrated VC (variable capacitance) micromotors [35]. The simple parallel-plate model is provided with these PC-design tools for calculation of electrostatic drive torque for three different micromotor structures [36]. MPPM Micromotor Design Model (the modified analytical parallel-plate capacitance model) takes into account the edge effect of both the rotor and stator poles for actual estimation of total equivalent circuit capacitance in the rotor plane [35]. The three-dimensional field model of a variable capacitance electrostatic micromotor is presented and the underlying analysis problem is solved by means of the finite element method [37]. Pelikant et al. [38] proposed the numerical algorithm to solve dynamic problems using field circuit analysis. Two dual finite element formulations for calculating 3D electrostatic field is presented and to apply virtual work principle for obtaining the local force distribution [39]. In order to apply numerical optimization algorithms, an automated finite element modeling is implemented into the design process. The number of stator and motor poles, their width and the particular rotor position are the only data necessary for the automated mesh generation [40]. Starting voltage, step responses, switching and continuous operation were all simulated by four separate blocks [41]. In addition, overlapping element method (OLM) for modeling the movement in a 3D FEM code in order to evaluate these parameters for different successive positions of the rotor is presented [42,43].

Numerical models based on finite element methods have also been developed for performing contact analysis. Zhang and Meng [44] have developed a mathematic model to calculate the area of contact and stresses and strains in the contact region between the rotor and bearing hub in electrostatic micromotor under the effect of electrostatic force. A schematic diagram of the mathematic model is shown in Fig. 6. The mathematic model describes the contact dynamics of the rotor and bearing hub when the rotor rotates at a high speed, which obtains the drive torque from the normal electrostatic force. In addition, the stress and strain in the contact area, which are the same as the stress and strain in bending, are deduced under the effect of micro-scale. Both of them are proportioned to a constant. The von Mises stress in contact region and the strain distribution in $z$-direction under different applied voltages are illustrated in Figs. 7 and 8, respectively. The model and the finite element analysis can be helpful for micromotor design.
3.2. Experimental methods to study failure mechanism

3.2.1. Atomic force microscopy (AFM)

The atomic force microscope (AFM), developed by Gerd Binning et al. in 1985 is a powerful tool for investigating surface topography, adhesion, friction, wear, lubrication, and several other surface phenomena on a micro-scale. The atomic force/friction force microscope (AFM/FFM) is an ideal instrument for direct measurements of surface phenomena on MEMS devices, components, and their surfaces. Sundararajan and Bhushan [45] have presented a novel technique (Fig. 9a) to measure the static friction force (stiction) encountered in surface micromachined polysilicon electrostatic micromotors using an AFM. An AFM tip is pushed against a rotor arm of the micromotor so as to generate lateral deflection of the tip, which is measured by the AFM. The maximum value of the lateral deflection obtained prior to rotor movement rotation is a measure of the static friction force of the micromotors (Fig. 9b).

3.2.2. Testing vehicle

The biggest reliability concern for micromotors is the connection of the motor to the substrate. The main wear mechanism in silicon micromotor was identified as adhesive wear and friction [46]. At Sandia National Laboratories [32], a special micromotor was developed, which was capable of providing a significant amount of force on the structure under investigation (Fig. 10).

3.2.3. Focused ion beam (FIB)

The FIB tool is widely used in microelectronics for circuit reconfiguration [47]. The FIB permits to mill materials locally and then to cut or uncover lines protected by an insulator layer. FIB is used to create precise cross-sections in MEMS. The first application of this technique consists of preparing samples for layer thickness measurement.

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Fig. 8. The strain distribution in z-direction under different applied voltages.

Fig. 9. (a) Schematic of the technique used to measure the force required to initiate rotor movement using an AFM/FFM. (b) Raw lateral deflection and normal deflection data obtained using an AFM against a rotor [45].

Fig. 10. The Sandia micromotor test vehicle to investigate wear mechanisms [32].
measurements [48]. Fig. 11 shows the cross-section of an unreleased electrostatic micromotor realized in MUMPs. In such a design, the size of the oxide layers governs the mechanical clearance between the rotor and the hub. Here, the distance between the rotor and the hub is approximately 15% thinner than the standard layer thickness.

3.2.4. Lift-off
Lift-off is necessary in micromotors when one wishes to observe the underneath surface of it. Lafontan et al. [47] presents the FIB (focused ion beam) tool for the application of the lift-off technique. The technique is applied to a failed electrostatic micromotors for observing arcing damages. Firstly, the rotor was liberated from the hub through FIB milling (Fig. 12). Then the rotor was flipped and observed at SEM. Fig. 13 shows the back-side view of the rotor and a close-up view of weld poly silicon induced by arcing.

4. Solving methods to reduce the failures

4.1. Selecting materials
The primary performance and reliability metrics considered are the actuation voltage, speed of actuation, actuation force, stored energy, electrical resistivity, mechanical quality factor, and resistance to fracture, friction, fatigue, shock, and stiction. The materials properties governing these parameters are the Young’s modulus, density, fracture strength, intrinsic residual stress, resistivity, and intrinsic material damping [49]. Srikar and Spearing [49] plotted the relationship between the Young’s modulus and fracture strength, as shown in Fig. 14. The nominal values shown in Fig. 14 are intended to guide the initial choice of materials only.

Material properties may significantly affect the reliability of future products as MEMS designs become increasingly complex and the number of commercial applications increases [50]. Processing considerations have made silicon a popular choice as the material for
the micromotors, but recent advances in micromachining techniques enable the integration of a number of different metals, alloys, ceramics, glasses, and polymers into MEMS [51]. Examples of materials used to fabricate electrostatic micromotors include silicon dioxide, nickel, diamond, silicon carbide, and polysilicon. Materials are important to reduce friction and wear in micromotors and accordingly improve the reliability and extend lifetime. Diamond-like carbon (DLC) is also applied to reduce friction and wear thin films of silicon nitride. As the MEMS materials set continues to expand, there is a clear need for a rational and systematic approach toward the selection of materials in design of micromotors.

4.2. Reasonable designs

The design of a micro-device in MEMS is of great important. Drive systems, in particular, rotating electrostatic micromotors are fabricated by surface micromachining using polysilicon with a thickness of only a few micrometers. The LIGA method and PMMA (polymethyl methacrylate) molds can be used to fabricate the wobble micromotor [63]. In addition, the polysilicon center pin process, the polysilicon flange process, the selective CVD tungsten process, the diamond-like carbon (DLC) process, the LIGA process with sacrificial layer, and the three-mask tungsten process have been published for the fabrication of electrostatic micromotors [64–67].

There are three micromotor parameters that affect the final operational device characteristics: the motor air-gap size, bearing radius and bearing clearance [52]. Holding all other MEMS parameters constant, reducing the air-gap size increases the motive torque. Increasing the bearing radius increases the bearing frictional force.

For a centre-pin bearing salient-pole micromotor, performance is optimized by minimizing the bushing and the bearing radii. The bushing frictional torque is proportional to the bushing radius. For the wobble micromotors, ratio and motive torque are proportional to the bearing radius. In this case, increasing the bearing radius leads to enhanced motive torque which is expected to be larger than the increase in the bushing friction torque, resulting in an increase in the micrometer net output torque.

In general, both salient-pole and wobble micromotor performance is enhanced by minimizing the bearing clearance [52,53]. For the salient-pole micromotors, smaller bearing clearances result in reduced bearing friction. For the wobble micromotor, smaller bearing clearances result in increased motive torque. The smallest bearing clearance reported for polysilicon micromotors is 300 nm [53]. For micromotors made by the LIGA process if the structural height exceeds 0.1 mm the bearing clearance can be hardly smaller than 250 nm [52]. It is important to have very small bearing clearances in such micromotors.

4.3. Surface lubrication

4.3.1. Selecting lubrications

Since the rotors must be supported on bearings, the long-term reliability of these bearings are taken into consideration. It is generally known that most micromotors cannot be rotated as manufactured and require some form of lubrication. The effects of environmental conditions on these forces must also be understood and effective lubrication methods for micromotors need to be considered.

The atomic force microscope and friction force microscope (AFM/FFM) is an ideal instrument for direct measurements of the static friction force found in surface micromachined electrostatic micromotors [45]. Octadecyltrichlorosilane (OTS) has shown the ability to reduce friction [54]. In addition, using AFM, boundary lubrication properties of perfluoropolyether (PFPE) lubricants and self-assembled monolayer lubricants have been conducted previously [55]. Several types of PFPE lubricants are available for micromotors, such as Z-15 and Z-DOL [56].

4.3.2. Self-lubrication

Another possibility of decreasing friction, wear and stiction in micromotors is self-lubrication. For such purposes ultrathin films (below 300 nm thick) can be applied if the lubricants incorporated into the film's material.

The hard films exhibit very good mechanical and wear properties. For the manufacture of the films a special, very cheap and simple technique of glow discharges stabilized by a dielectric barrier is applied [57,58]. These
ultrathin films (below 300 nm thick) mainly consisting of silicon dioxide or silicon nitride are produced by polycondensation of tetraethoxysilane (TEOS) or hexamethyldisilazane (HMDSN) vapours, respectively, in mixtures with argon, oxygen, nitrogen or ammonia.

Both the self-lubricating ultrathin films of silicon dioxide and silicon nitride containing organic substances playing the role of chemically incorporated lubricant seem to be very effective solutions of friction, wear and stiction problems for micromotors in MEMS.

4.4. Gas-lubricated bearings

The application of special gas-lubricated bearings was also proposed [59]. Since the rotors must be supported on bearings, there is concern about the long-term reliability of these bearings. Fukui et al. [60] firstly investigated the micromotor bushings and quantitatively estimated the self-acting bearing effects of micromotors using a molecular gas film lubrication equation. Chen et al. [61] considered the coupling effects of roughness and gas rarefaction on the micromotor bushings and found that these two terms are significant in the analysis and design of micromotors. On the other hand, rarefaction effects tended to reduce the effects of roughness. We have investigated the gas-lubricated sliding bearing beneath micromotor bushing with slip model. The schematic illustration of electrostatic micromotor is shown in Fig. 15. The pressure distribution for various slip models of the step slider bearing with $A = 200$ and $x_{\text{step}} = 0.4L$ and load carrying capacities versus inverse Knudsen number are illustrated in Figs. 16 and 17, respectively. Slip effect reduces the pressures and then results in the descending of load carrying capacity with increasing bearing number $A$. The maximum pressure and load carrying capacity point at the step declines along the slider bearing length and moves backwards with increasing $A$ and $x_{\text{step}}$. Therefore, the slip effect is
significant in the analysis and design of micromotors and should not be neglected in slip and transition regimes. The pressure or load carrying capacity generated beneath the bushings can support the rotor, and thus decrease the possibility of friction, contact and wear in micromotors.

5. Conclusions

The electrostatic micromotor technologies are still in the initial stage of the development, particularly in its applications and reliability. Our knowledge of the physics of failure mechanisms in the micro-domain is still very limited. Currently there is hardly any dedicated equipment for the study of micromotors reliability. The future of electrostatic micromotors will be marked by new actuation principles, design methods and tools, modeling and simulation methods, control systems, fabrications, and applications that have sophisticated requirements concerning small size, lower power consumption, low weight, high speed, high torque, high shock resistance and high mechanical cut-off frequency. Still there are a set of unsolved problems today, friction, wear, stiction and fatigue which reduce the lifetime and reliability and testing methods.

In conclusion, the research of electrostatic micromotors reliability is a fascinating field of high importance for the successful application in MEMS technology. Far too little is known about micromotor reliability at present compared to the amount of devices already available as prototypes in laboratories all over the world and likely to become available in the near future. Many of these will only see a successful commercialization when the relevant reliability issues can be dealt with. The research of the failure modes and mechanisms of micromotors and new solution methods is therefore a challenging, but very rewarding task.

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References


