Sensors and Actuators A 177 (2012) 1–9

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Design and characterization of MEMS micromotor supported on low friction liquid bearing

Mei Lin Chan[a], Brian Yoxall[a], Hyunkyu Park[a], Zhaoyi Kang[b], Igor Izyumin[b], Jeffrey Chou[b], Mischa M. Megens[b], Ming C. Wu[b], Bernhard E. Boser[b], David A. Horsley[a,*]

[a] Department of Mechanical and Aerospace Engineering, University of California at Davis, Davis, CA 95616, USA
[b] Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA, USA

ARTICLE INFO

Article history:
Received 16 April 2011
Received in revised form 3 August 2011
Accepted 4 August 2011
Available online 25 August 2011

Keywords:
Micromotor
Liquid bearing
Micromachining
Hydrophobic
Torque
Magnetic drive

ABSTRACT

This paper examines the performance of rotating microdevices incorporating a liquid bearing to couple a rotating element to a fixed substrate. Liquid bearing technology promises to significantly improve the durability and lifetime of micromechanical motors. Here, the fluid is confined between the rotor and stator using surface patterning of a hydrophobic layer. Magnetic actuation of 10 mm diameter silicon rotor is used to characterize the liquid bearing motor at rotation rates up to 1800 rpm. Bearings with fluid thickness from 20 to 200 μm are characterized. A minimum torque of 0.15 μN-m is required to initiate rotation. At rotation rates above 720 rpm, the rotor wobble is less than ±1 mrad and the bearing exhibits viscous friction with a drag coefficient of 1.2×10^{-3} μN-m/rpm. The drag performance of the disk-type liquid bearing using H_2O as the fluid is approximately 15 times lower than that demonstrated in a micro-ball bearing supported rotor.

1. Introduction

Surface tension and friction are dominant forces at small length scales. In this expanded effort based on the previous work [1], we exploit surface tension to overcome friction limitations in rotating microdevices by supporting a freely-rotating payload on a liquid rotary bearing. There are many instances of MEMS rotary motors in the literature. Examples include center-pinned wobble motors that have been actuated electrostatically [2,3], ultrasonically [4] and magnetically [5] as well as motors incorporating micro-ball bearings [6]. A systemic problem with solid–solid contacts between the rotating parts and frame elements is friction. To minimize the effect of friction and wear in macroscale devices, fluid lubricating layers are often used to remove direct solid–solid contact. These lubricating layers take the form of externally pressurized gas-lubricated hydro-dynamic bearings [7] and "air" bearings created through electrostatic or magnetic suspension [8,9]. These support mechanisms often require complex manufacturing processes with tight fabrication tolerances and complicated control schemes.

Here, instead of using pressurized fluid to provide the thrust for bearing support, surface tension between a thin liquid film and the patterned rotor and stator surfaces acts as the support mechanism. Although the liquid bearing principle has been demonstrated [10,11] using electrowetting as the driving mechanism, little quantitative performance data or analytical modeling have been presented to date. As demonstrated herein, liquid bearing technology is wear-resistant, capable of supporting both static and dynamic loads, and is self-centering.

In this work, the focus is on the design and characterization of the liquid bearing structure. The bearing technology can be used with various actuation methods but magnetic actuation was chosen here over electrostatic actuation due its simpler fabrication and lack of pull-in instability. Using methods similar to earlier magnetic micromotors [5,12], permanent magnets are assembled onto the silicon rotor and external coils are used to generate magnetic flux, allowing rotation rates over 1800 rpm. We present experimental data on the load-bearing capacity, viscous drag characteristics and wobble of the liquid bearing micromotor using water and ethylene glycol (EG) as the liquid layer in three different bearing geometries (disk, ring and full coverage). Static and dynamic loading characteristics of the liquid bearing motor are also determined. A self-centering characteristic observed in one of the bearing designs is analyzed and liquid bearing packaging and lifetime issues are addressed.

* Corresponding author at: Department of Mechanical and Aerospace Engineering, One Shields Avenue, Bainer Hall, Davis, CA 95616, USA. Tel.: +1 530 752 1778; fax: +1 530 752 4158.
E-mail address: dahorsley@ucdavis.edu (D.A. Horsley).

0924-4247/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2011.08.003

2. Operating principle

Fig. 1 shows a schematic drawing of the liquid bearing rotor and the experimental set-up used to magnetically actuate the liquid bearing motor. The bearing geometry is defined by patterning the surfaces of the rotor and stator with a 2 μm thick hydrophobic amorphous fluorocarbon layer (Cytop, Asahi Glass Co.). The contact angles of water and EG on the Cytop surface are ∼99 and ∼94 degrees, respectively. The relatively high surface energy of glass and silicon allows the bearing liquid to wet the exposed surfaces, while the hydrophobic Cytop layer pins the bearing edges to a fixed location, as illustrated in Fig. 2a.

Surface tension effects provide centering and load carrying capability. The bearing thickness, h, investigated in this work lies in the range between 20 and 200 μm thick, much smaller than the capillary length, l_c, of the liquids ($l_{c,\mathrm{H_2O}} = 2.7$ mm, $l_{c,EG} = 2$ mm) in order to ensure that surface tension dominates over gravitational force on the fluid.

In response to a transverse force applied to the right edge of the rotor (see Fig. 2b), the contact angle of the liquid bearing changes and the restoring force due to surface tension is:

$$F_{res} = \sqrt{2}R\gamma_{LV}(\theta_R - \theta_L) \quad (1)$$

where γ_{LV} is the fluid surface tension ($\gamma_{LV,\mathrm{H_2O}} = 72.8$ mJ/m^2, $\gamma_{LV,EG} = 47.7$ mJ/m^2), θ is the contact angle and the subscripts R and L denote the contact angle at the right and left edges of the rotor and R is the bearing radius. For the bearing geometry under test, and assuming a contact angle offset $(\theta_L - \theta_R) = 10^\circ$, the restoring force, $F_{res} \approx 100$ μN, allowing the bearing to support a maximum transverse load equal to approximately 10% of the rotor's weight. The rotor mass scales as R^2 while the transverse retention force scales as R, so the bearing's ability to support transverse forces improves dramatically as the motor radius decreases, and suggesting that a motor with a 1 mm diameter rotor could operate in a vertical orientation.

For motion in a direction normal to the rotor face, as illustrated in Fig. 2c and d, a lifting force, F_{sup}, or an adhesion force, $F_{pulloff}$, results from both Laplace pressure and surface tension:

$$F_{normal} = \frac{2\pi R^2 \gamma_{LV}}{h}\cos\theta + 2\pi R\gamma_{LV}\sin\theta \quad (2)$$

where h is the bearing thickness. The contact angle between the liquid bearing and the surface, θ is assumed to be the same at all edges of the disk and is critical in determining the forces acting on the rotor.

A liquid bearing with low viscosity, μ ($\mu_{\mathrm{H_2O}} = 1$ mPa s, $\mu_{EG} = 16.1$ mPa s), allows the rotor to operate in a low friction domain. The viscous friction characteristics of the liquid bearing are a function of fluid thickness and radius and are modeled by the viscous drag coefficient, b:

$$b = \frac{\mu\pi R^4}{2h} \quad (3)$$

Static friction properties of the bearing have a more complicated origin, depending on both the curvature of the bearing edge and roughness created by imperfections of the bearing boundary.

3. Design and fabrication

The fabrication process for both rotor and stator is detailed in Fig. 3. The stator is fabricated from a 700 μm thick glass substrate while the rotor is 10 mm diameter disk made from a 300 μm thick silicon wafer. Fig. 3j–m shows the stator layer fabrication procedure in which a photoresist liftoff process is used to pattern the Cytop film that defines the shape and size of the liquid bearing. A 3 μm thick positive photoresist (Megaposit SPR220-3, Rohm and Haas) is spin-coated and patterned by photolithography to define the circular confinement region for the liquid bearing. The Cytop thin film is then spin-coated at 1500 rpm onto the wafers. After hard baking at 110 °C for 10 min, unnecessary Cytop and photoresist patterns are stripped in acetone, then rinsed in methanol and D.I. water.

The rotor fabrication begins with a double side polished 4-in. silicon wafer. A Cytop layer is first defined on the bottom surface of the wafer using liftoff as described above. On the top side of the wafer, a trench is etched using deep reactive ion etching (DRIE) to 80 μm depth to define the housing for the magnet. To ensure concentricity of the bearing pattern on the rotor, the rotor's cylindrical shape is lithographically aligned to the bearing pattern on the backside of the wafer using 10 μm thick photoresist (KMPR 1005, MicroChem) and DRIE is used to etch through the 300 μm thick wafer.

A 1.5 mm NdFeB magnet cube with magnetic moment, m, of 4.1×10^{-3} A m^2 is centered and mounted on top of the rotor. The mass moment of inertia of the rotor is 6.96×10^{-10} kg m^2 and 6.86×10^{-10} kg m^2 with and without the magnet, respectively; while the total weight of the rotor-magnet structure is ∼90 mg. Fig. 4 shows side and bottom views of a complete (stator/liquid-bearing/rotor) device assembled using a vacuum pick-and-place technique. In Fig. 4a, the side view of the assembled rotor shows the liquid bearing colored with a red dye to help visualize position. The bottom view is taken through the glass stator focusing on the liquid bearing and the bottom of the rotor. This view highlights the single-droplet liquid bearing structure with 10 μl of liquid confined within the 6 mm diameter annular patterned Cytop layer. The outer ring of electrodes on the rotor was designed for electrostatic driving but was not employed in this work.

The mechanical performance of the liquid bearing micromotor was characterized using magnetic actuation to spin the rotor. Two orthogonal pairs of Helmholtz coils are driven with currents that are 90° out of phase, at matched amplitudes, to create a rotating magnetic field with uniform magnitude in the range of $B = 1$ mT. The frequency of the coil signal, Ω, determines the motor rotation rate while the field amplitude provides control over the applied torque.

4. Performance

4.1. Static pull-off force measurements

As described by Eq. (2), surface tension creates either adhesive or repulsive forces to: (1) prevent separation of rotor from stator or (2) support the rotor. In the case where the motor is inverted and gravity pulls the rotor away from the stator, as illustrated in Fig. 2d, a concave-shaped meniscus bridge forms between the hydrophilic part of the stator and rotor. Referring to Eq. (2), the concave shape of the liquid interface ($\theta < 90^\circ$) results in negative Laplace pressure inside the bearing liquid. This negative pressure results in an intrinsic adhesive force between the stator and rotor and retains the rotor in place. On the other hand, when the motor is upright, the gravitational force compresses the bearing and the liquid interface assumes a convex shape. A convex meniscus interface angle ($\theta > 90^\circ$) creates a positive Laplace pressure and repulsive F_{sup}, as illustrated in Fig. 2c. The contact angle between the fluid and Cytop surface defines $\theta_{\max}$ and thus $F_{sup,max}$ for the bearing.

A quasi-static loading measurement using an electronic microbalance (A&D HR202i) with a sensitivity of 0.01 mg was conducted to determine both the tensile pull off force required to separate the rotor from the liquid surface and the compressive load carrying capability of the rotor. The assembled micromotor of the disk bearing design was placed inside the microbalance. Care was taken to run the experiment in a saturated vapor pressure environment by placing a beaker of supersaturated salt solution in