DEVELOPMENT OF A HYBRID GAS / BALL BEARING SUPPORT MECHANISM FOR MICROTURBOMACHINERY

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Abstract: The development of a hybrid gas / ball bearing support mechanism for spin-down friction testing of microfabricated turbomachinery is presented in this paper. Radial in-flow microturbines, with a 10mm diameter rotor, were fabricated with encapsulated microball bearing supports. With the addition of a hydrostatic thrust bearing, turbine speed and thrust force have been decoupled allowing the acquisition of relevant spin-down data. This is the first demonstration of a microball bearing supported device with independent control of speed and thrust loading, a necessity for comprehensive characterization of bearing friction. Development of the microfabricated turbines and experimental apparatus is presented along with the demonstration of successful spin-down data acquisition at various loads, showing a linear relationship between dynamic bearing friction and rotational speed.

Key Words: microturbine, microball bearings, spin-down, rolling friction

1. INTRODUCTION

Microball bearings provide a simple, stable, and robust support mechanism for PowerMEMS devices. With inherent tribological and system-level benefits, MEMS ball bearings represent a compromise between the more extensively studied gas-lubricated and sliding contact bearings. While gas-lubricated systems have superior speed and friction characteristics [1], microball bearing support mechanisms are notably simpler to fabricate and operate. Similarly, microball bearings provide increased tribological performance over sliding contact bearings, where friction and wear seriously impact the performance and life of such devices.

Accordingly, our group has demonstrated several ball-bearing supported devices exploiting these benefits. While microball bearings have been shown to be reliable and robust support mechanisms, accurate friction and wear modeling is necessary for high performance applications. The major limitation to characterizing friction in theses devices is the coupled nature of the actuation and thrust loads. In the micromotors and microturbines presented at *Hilton Head '06* [2] and *Transducers '07* [3-4], the normal load on the bearings was solely dependent on the actuation force. These forces have been decoupled in the microturbines developed for this work (shown in Fig. 1) allowing comprehensive spin-down friction testing at various thrust loads.

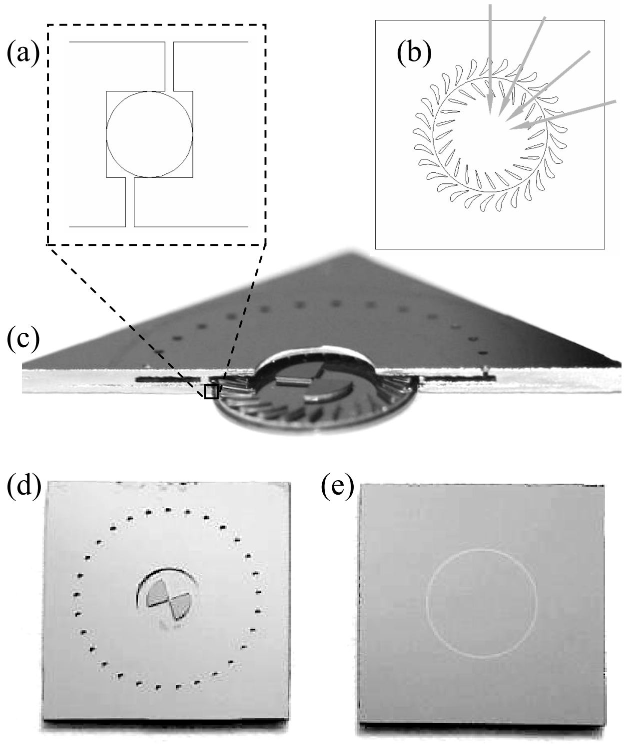

Fig. 1: Ball-bearing supported microturbine showing (a) the bearing geometry, (b) the blade design showing flow direction and optical photos of (c) the device cross-section, (d) top side with ports and speed bumps, and (e) the bottom side thrust bearing surface.

2. DEVICE

To investigate the effects of speed and thrust load on a novel MEMS encapsulated ball bearing design, microturbines supported on a hybrid gas / ball bearing have been developed. Figure 1 shows the geometries of the various device components. To minimize friction and wear, the encapsulated microball bearing fabrication process developed by Waits *et al.* [5,6] was modified to provide planar (Fig. 1a), rather than point, contact between the silicon race and steel microballs. Figures 1b & 1c show the radial-inflow blade design and a cross-section of the fabricated device, showing the 10mm diameter rotor. The topside of the device consists of a radial array of inlet orifices and a central outlet where the rotor speed bump structures can be seen (Fig. 1d). The bottom side of the device (Fig. 1e) shows the underside of the encased rotor which acts as a thrust bearing surface. By pressurizing the backside of the device the rotor is lifted into proper ball bearing contact and spun with pressurized nitrogen passing through the radial-inflow microturbine.

3. FABRICATION

The microturbine fabrication process consists of wafer-level construction of encapsulated rotors followed by die-level temporary bonding of a capping layer to create internal flow paths. First, the microball housing is defined with a nested deep reactive ion etch (DRIE) in a pair of silicon wafers (Fig. 2a,b). A gold/tin bonding layer is evaporated though a shadow mask and approximately ninety 440C stainless steel microballs ($\varnothing$=285μm) are placed in the circular bearing housing (Fig. 2c). The wafers are eutectically bonded (Fig. 2d) using the method described in detail in [5,6]. The wafer stack is diced and individual die are deep-etched using patterned SiO_2 masks to define turbine structures and release the rotors (Fig. 2e). A silicon capping layer is created with a shallow recess to provide clearance for the spinning rotor (Fig. 2f) and a through-etch is used to define inlet and outlet ports (Fig. 2g). Finally, the released rotor and capping layer are bonded using a temporary photoresist layer (Fig. 2h,i). As a result, the capping layer can be de-bonded between tests to examine the turbine and bearing structures.

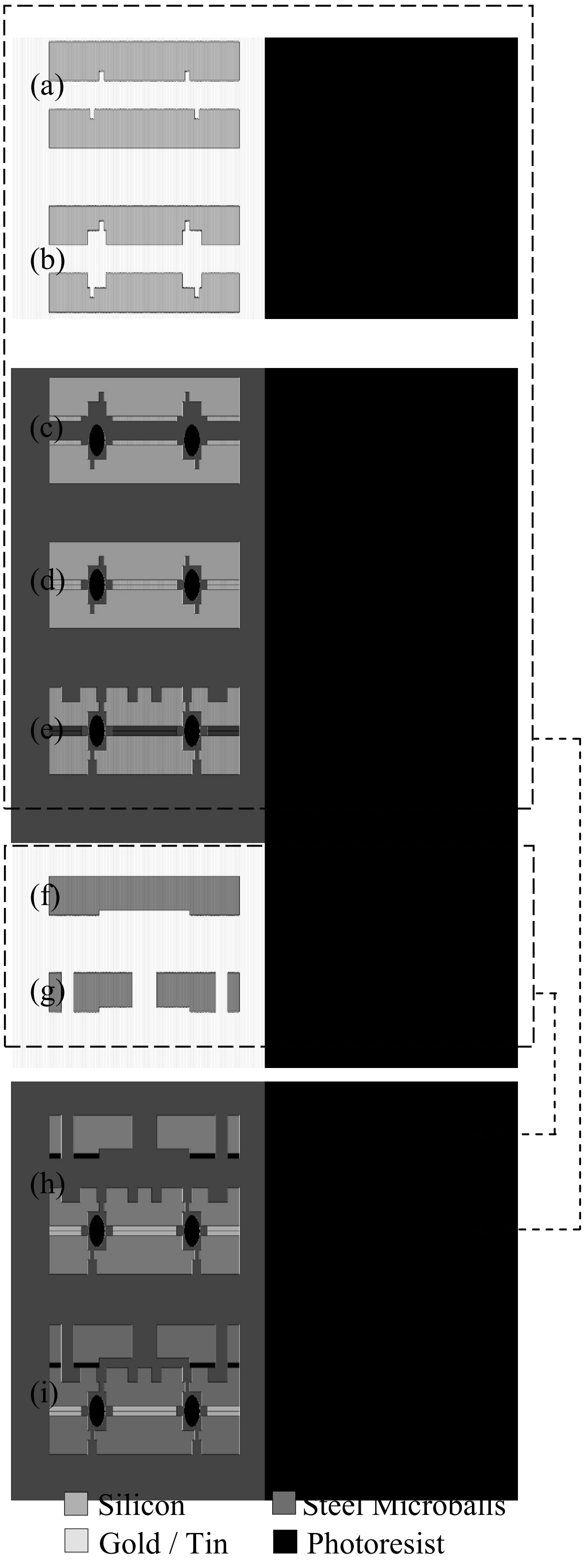

Fig. 2: Multi-wafer silicon microturbine process flow showing (a-e) the encapsulated rotor fabrication, (f-g) the capping layer fabrication, and (h-i) the final bonded die.

4. TESTING AND RESULTS

Complete characterization of dynamic friction in the planar-contact encapsulated microball bearings shown in Fig. 1 requires independent control of bearing speed and thrust load. The decoupling of speed and thrust load during spin-down testing is achieved using a hydrostatic thrust bearing defined by a novel packaging assembly. Figure 3 shows a packaged device being tested and Fig. 4 provides schematic representations of the device cross-section and operation.

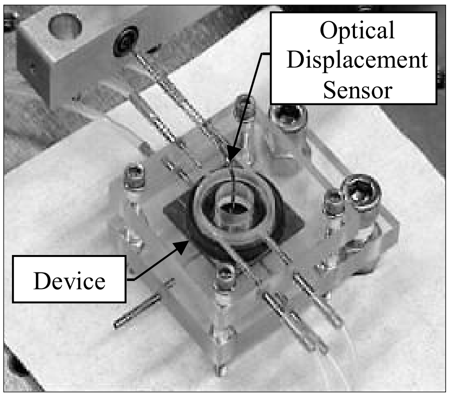

Fig. 3: Photo of a packaged microturbine showing various pneumatic connections and the optical displacement sensor.

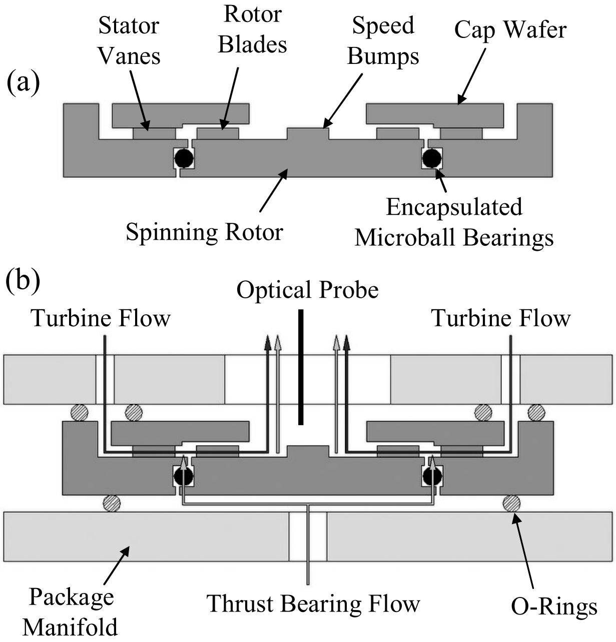

Fig. 4: Schematic showing (a) the microturbine cross-section and (b) the experimental operation of the device.

The microfabricated turbine is packaged between two plastic manifolds using rubber o-ring seals for fluid delivery as well as compliant support. The bottom side of the device is pressurized lifting the rotor into proper contact with the ball bearings. A desired thrust load is achieved using a high-sensitivity flow control valve and a transducer to monitor backside pressure. To actuate the turbine, compressed nitrogen is provided through the topside manifold while an optical displacement probe tracks the rotation of etched speed bump structures. The turbine flow is abruptly shut off and the angular trajectory is acquired as the rotor decelerates under this influence of bearing friction alone.

During turbine actuation, the thrust bearing pressure is increased substantially due to the nature of the microturbine design. High-pressure turbine flow passes over the rotor periphery and elevates the backside pressure from the desired thrust load. After the turbine flow is shut off, the backside pressure equilibrates to the pre-set value and the rotor decelerates under a constant thrust force thereafter. Figure 5 shows this behavior for one of the devices tested in this work.

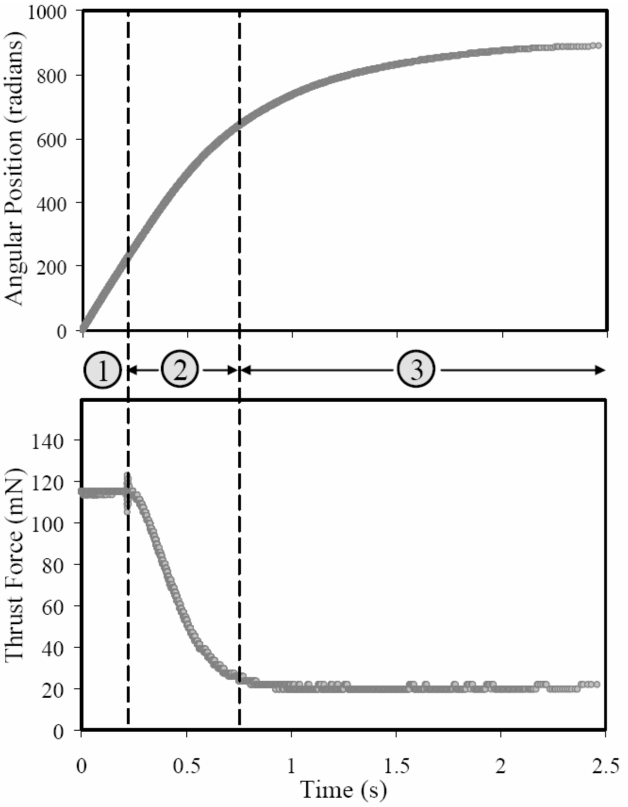

Fig. 5: Dynamic turbine response during spin-down data acquisition, showing three stages.

The spin-down response of the microturbine, shown in Fig. 5, can be separated into three distinct stages. Initially, the turbine is spinning at a constant speed (10,000rpm at 7.5slm turbine flow) corresponding to a linear increase in angular position and a constant thrust force (stage 1). The turbine flow is shut off and the thrust force decreases dramatically as the rotor begins to slow down (stage 2). Finally, stage 3 corresponds to the period after the thrust load equilibrates to within 10% of the pre-set desired value (20mN). Spin-down data is acquired during stage 3 as the rotor continues to decelerate under a specified constant thrust force.

To characterize the effects of speed and load on dynamic bearing friction, this testing procedure is repeated for several thrust loads. Figure 6 shows spin-down data acquired at various thrust forces, showing faster spin-down at higher loads, as would be expected. The trajectories fit well to an exponential function (with coefficients A and B), which corresponds to a linear relationship between friction torque (angular acceleration) and bearing speed (angular velocity).

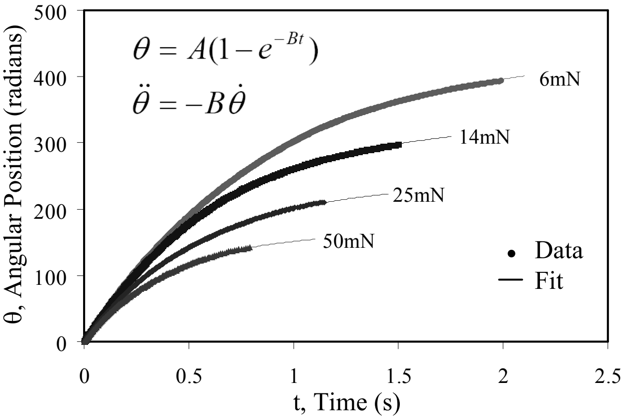

Fig. 6: Spin-down trajectory data for various thrust loadings, showing an exponential trend.

By analyzing the resulting spin-down trajectory, the experimental devices and apparatus developed in this work can be used to extract a comprehensive empirical model of dynamic bearing friction. Future publications will focus on modeling bearing friction at speeds and thrust loads relevant to the microball bearing supported actuators, motors, turbomachinery and pumps being developed by our group. Additionally, this work provides a platform to investigate the effects of wear, life cycle, and solid film lubrication in encapsulated microball bearings.

5. CONCLUSION

A hybrid gas / ball bearing support mechanism for MEMS-fabricated turbomachinery has been developed for the purpose of characterizing dynamic friction in encapsulated microball bearings. The fabrication and characterization of a microturbine with decoupled actuation and thrust forces has allowed the collection of relevant spin-down data necessary for comprehensive friction modeling. This is the first microball bearing supported device capable of independent control of speed and thrust load. Initial results show a linear relationship between bearing friction and rotational speed. This work will serve as the basis for the development of an empirical model of dynamic friction in encapsulated microball bearings.

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