Off-the-Shelf MEMS for Rotary MEMS

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ABSTRACT

This work demonstrates the utilization of an Off-The-Shelf (OTS) MEMS accelerometer to accurately and repeatedly determine the onset of instability and perform *in situ* diagnostics of a high-performance rotary MEMS device. The accelerometer is shown to provide high sensitivity, wide bandwidth vibration measurements when bonded to the stator of a MEMS device. Vibration sensing is augmented with optical displacement sensors to create a multi-modal sensor platform. The sensor suite has been used to characterize the rotor instability for rotor speeds from 10-20 krpm, diagnose imbalance acceleration with sensitivity down to 0.001 g, determine rotor wobble of with an accuracy of <500 nm, and monitor system resonances through the speed range of 5-20 krpm. The data provided by the on-chip accelerometer can be used in feedback systems to optimize device performance and increase operational lifetimes.

INTRODUCTION

Micro-ElectroMechanical Systems (MEMS) utilize semiconductor fabrication technologies to integrate mechanical components with electronics on a single chip. MEMS technology has progressed since the early 1990s from very simple systems with elementary electronics [1], to fully integrated sensor platforms [2] employed in car airbags and *Nintendo Wii* controllers. One such example of a mature MEMS device is the accelerometer.

The MEMS accelerometer has become a critical sensor for scientific and industrial process monitoring and control. This includes consumer product applications such as motion sensing and image stabilization, structural applications including monitoring of bridge loading and earthquakes, and industrial applications in vibration-based condition monitoring of machines. The ubiquity of the accelerometer is due to the high sensitivity, high shock load resistance, and low mass of the sensors.

Complex rotary MEMS have been explored for such as power conversion [3], actuation [4], and sensing [5]. These devices serve as micro-scale analogues to their macro-scale counterparts. On the macro-scale, such machines undergo constant diagnostics to assure operation is in a low-wear regime and the device is taken offline before critical failure. On-board diagnostics of this nature can also be done within microsystems by integrating high sensitivity sensors with the actuator.

Recently, rolling bearing technology has been extended to the field of MEMS in the demonstration of high-performance linear and rotary micromachines. A

microball bearing consists of deep-etched silicon raceways containing OTS stainless steel microballs. The microball bearing serves as a middle ground between the high-speed but complex levitated bearings, and the simple low-speed sliding bearings.

Four operating parameters were selected as the focus of the on-chip diagnostics: *bearing instability*, *imbalance diagnosis*, *rotor wobble*, and *system resonances*. It should be noted that while a microball bearing supported device was used to demonstrate the capability of the on-chip accelerometer, any rotary MEMS device could utilize this platform for similar analysis.

EXPERIMENT

A microfabricated silicon turbine supported on stainless steel microball bearings ($\phi=285\ \mu\text{m}$) serves as the platform for the diagnostic testing and characterization (figure 1). The friction and performance of the microturbine has been thoroughly characterized in [6, 7]. The accelerometer (*Analog Devices, ADXL325*) is monitored through custom packaging that integrates turbine pneumatic actuation and sensing elements with electrical components. Testing is performed in a vibration-isolated isochoric chamber.

Figure 1: Photograph of silicon microturbine with attached OTS MEMS used for vibration sensing.

The silicon microturbine supported on microball bearings from [7] was modified to include backside contact metallization, so that various accelerometers could be attached to the surface to ensure solid mechanical contact. The microturbine rotor is actuated to speeds up to 20 krpm with compressed N_2 gas flow. The packaging for the microturbine included manifold layers for turbine actuation and pneumatically controlled thrust load, pressure sensors, optical displacement sensor, as well as electrical contacts for accelerometer input and output voltages. The packaging of the test device segregated turbine flow and a thrust plenum, allowing for the decoupling of thrust and actuation loads.

The accelerometer used to measure mechanical vibrations has a bandwidth of 1.5 KHz and sensitivity and of ± 5 g's. The sensor has the potential for 3-axis acceleration monitoring, although it was found that a majority of the useful information came from the axis parallel to the radial direction relative to the rotor axis of rotation. Electrical contact was made via low-stiffness, spring-loaded pins to minimize vibration dampening.

An optical displacement sensor (*Filtec, D-6*) was utilized to measure out of plane displacement around the periphery of the rotor (wobble) to augment the accelerometer measurements. The optical sensor has a displacement sensitivity of 380 nm over a range of 51 μ m. This wobble is induced by the imperfect depth profile of the raceways supporting the microball bearings. The deep-reactive ion etched raceways show a depth variation of 0.25% around the 10 mm diameter trench which sets a minimum for the potential wobble of the system.

Significant measures were taken to assure the measured accelerations and wobble were isolated from the surrounding conditions. The microturbine made soft, elastomeric contact to its packaging. The package was suspended through another elastomeric contact above the floor of an isochoric chamber, all supported on a floating table. This was to assure that outside vibration did not translate to the device or *vice versa*.

DISCUSSION

Bearing Instability

All rotary devices have unstable operating regimes regardless of the bearing mechanism. In non-contact bearings, such as the microturbine reported by Frechette et al. [3], these instabilities arose from aerodynamic affects in the journal and thrust bearings. In the case of the microball bearings, instability arises from fabrication limiting the design to be a thrust bearing (parallel axis of rotation and primary load). The radial centripetal force acting on the rotating balls scales with $velocity^2$. The radial forces on the ball bearing will eventually encourage the ball to roll along the sidewall, rather than the intended thrust surface. The static friction between the ball and raceway counteracts the radial sliding. The rotor gradually loses load carrying capacity as it is accelerated to higher speeds unless a counter-acting normal load is imparted to keep the microballs in thrust-oriented operation. Using the accelerometer bonded to the microturbine, the instability-inducing load is determined for a range of speeds. Figure 2 shows the measured radial vibration, representative of increased ball-to-sidewall contact for a range of speeds and normal loads. These results correlate well with the calculated transition from thrust to radial operating regime (figure 2 inset).

The microturbine was not operated to a completely instable regime due to the potential for catastrophic failure. It is expected that if the normal load is decreased significantly below the thrust operating regime, the rotor will lose stiffness in the axial direction and wobble violently. On the other hand, excessive normal load will lead to accelerated wear rates in the raceway. The information from the accelerometer elucidates the need to balance speeds and loads for operation just below the onset of increased radial vibration.

Figure 2: Measurement of radial vibrations over a range of loads for set speeds. (inset) graphical representation of bearing operating regime calculated from first principles.

Imbalance Diagnosis

Micromachined rotors are very sensitive to fabrication-induced imbalances. The centripetal force imparted on the rotor is the product of the *mass*, *radius*, and *angular velocity*² of a single defect. A minor defect on a low speed micro-scale device becomes significant at the speeds of 50krpm to >1Mrpm intended for power-generating MEMS because of the velocity dependence. Such minor imbalances can arise from misalignment in bonding or lithography processes or etch non-uniformities. Early detection of a rotor imbalance is critical to preventing catastrophic device failure as it is accelerated to operating speeds.

The accelerometer has been used to diagnose an experimentally unbalanced rotor. For these tests, the rotor is operated at a set rotational speed and a time-averaged vibration spectrum is obtained. The unbalance is observed by taking the FFT of the vibration spectrum data. A peak is observed corresponding to 1X the operating speed. The microturbine is unbalanced by placing less than 1 milligram of polymer in a single location along the periphery of the rotor. Figure 3 shows the appearance of the fundamental peak for an unbalance rotor, and the baseline measurement taken before unbalancing and after the polymer is removed.

The force sensitivity limit of the on-chip accelerometer has been demonstrated as low as 0.001 g. To generalize the diagnostic capabilities, a sensitivity coefficient of $0.0098 (m_i \times r_i \times \omega^2)/m_r$ is defined where ω is rotor rotational velocity, m_r is the rotor mass, m_i and r_i are the mass and radius of the imbalance, respectively. This correlates to a minimum sensed mass imbalance of 0.2 μ g at the periphery of the rotor spinning at 50 krpm.

Figure 3: Imbalance is induced on the microturbine rotor and measured via the on-chip accelerometer.

Rotor Wobble

Rotational sensors and actuators need to accommodate for wobble when establishing sensitivity and operating parameters. On-rotor optics intended for long-range sensing will be extremely sensitive to unintended out of plane movement. Similarly, rotary gyroscopes are inherently sensitive to tilt in the rotational axis. Therefore, the authors determine rotor wobble is an important metric for rotary microsystems.

The out-of-plane movement of the rotor is monitored using an optical displacement sensor. From this data, the minimum normal load is discovered to insure minimum wobble operation. Figure 4 shows the peak-to-peak wobble versus normal load. While the microfabrication of the silicon microturbine is not the focus of this paper, it is important to note a necessary asymmetry in the raceways.

The microturbine test device is shown schematically in figure 4b. The device is comprised of three layers, a removable plumbing chip and two bonded chips that make up the rotor and stator. A complete fabrication scheme is detailed in [7]. In general, the fabrication consists of a raceway etch, bonding the balls in the raceway in-between two chips, and then releasing the rotor portion from the stator with top- and bottom-side etches. The top and bottom side etches are offset from one another. The implication of the offset release etch is that the balls make contact to flat surfaces in one direction of net normal load, and contact to etched corners in the unintended direction of normal load (figure 4b).

The rotor wobble data shows that at low normal loads, the actuated load and gravitational load are nearly balanced, so the rotor flutters between the two bearing orientations. Once the actuated load exceeds gravitational load, the rotor settles to a 1.2 μm peak-to-peak operation. The steady-state wobble is due to non-uniformity in the raceway etching process. The non-uniformity is expected to improve for smaller radii devices.

Figure 4: (a) Rotor wobble versus normal load. (b) cross-sectioned schematic of the microturbine highlighting two possible operating orientations.

System Resonance

Machines from the macro- to micro-scale undergoing a vibration load need to design around resonant operation modes. The resonance is characterized by a tendency to absorb significant amounts of energy when the input energy matches a natural resonant frequency of the mechanical system. Large amplitude oscillations are the result of operating in the resonant regime, and lead to accelerated wear and early failure. To counteract this potentially damaging operating regime, machines are often designed to operate sub- or super- resonant or incorporate damping to reduce oscillation amplitude.

The resonance of interest to micro-scale rotating machinery is the displacement of the rotor. Therefore the mechanical properties of the bearing, specifically the stiffness and damping, are the variables available to engineers to tailor micromachine operation to non-resonant modes. In the case of the microturbine from [3], the device was designed to operate above 1.4 Mrpm. To reach this speed, multiple resonant modes needed to be traversed, so active monitoring and control was necessary. Once it was determined that a resonant mode was being approached through optical displacement sensing, the pressure-drop across the air journal bearing was adjusted to change the spring constant, and thus the resonant frequency.

The resonance of the microball bearing supported turbine was discovered in this study using the on-chip accelerometer. The microturbine was repeatedly actuated to 20 krpm and the average vibration acceleration was obtained periodically. Additionally, the FFT of the vibration signal was obtained through the range of speeds. The amplitude of the FFT at the 1X fundamental frequency was extracted and plotted against the average acceleration in figure 5. A peak in the peak amplitude of the fundamental frequency can be observed at 11.3 krpm, which represents a resonant operating mode of the microturbine rotor. Past 11.3 krpm the fundamental peak height scales comparably with the average vibrational acceleration.

Figure 5: The fundamental peak amplitude and RMS average radial vibration. The fundamental peak height shows a peak at 11.3 krpm corresponding to a rotor resonance.

The resonant frequency of the rotor also contains information about the bearing stiffness at the resonant speed. Assuming that damping is minimal in the bearing, the rotor-bearing system can be treated as a simple harmonic oscillator, where the resonant frequency is equal to the root of the ratio of the spring constant to the mass. Based on the properties of the system, a resonance at 11.3 krpm (183 Hz) corresponds to a spring constant of 6 N/m in the bearing. Acceleration is transmitted from the rotor to the accelerometer via two possible paths: a non-contact perturbation of the air within the release trench and bearing cavity, or a contact of the ball bearing to the sidewalls of the rotor and stator. The spring constant calculated from the resonance confirms that the rotor displacement is only a perturbation of the air journal bearing and not squeezing the ball in solid-solid contact.

CONCLUSION AND FUTURE OUTLOOK

This work highlights the importance of *in situ* diagnostics for mechanical systems by using an on-chip, OTS, MEMS accelerometer to accurately and repeatedly determine the onset of instability and perform diagnostics of a high-performance rotary MEMS device. The vibration sensing mechanism was used to determine the ideal operating loads and speeds for the micro-ball bearing based microturbine. The centripetal force-induced instability in the thrust ball bearings was determined for

speeds from 5 krpm to 20 krpm. The device was unbalanced artificially and measured experimentally. The mechanical vibration sensing has been augmented by non-contact optical displacement measurements of wobble. Resonance was measured in the rotor and used to calculate the effective bearing stiffness. These features would have otherwise been difficult to accurately predict due to the complex, highly coupled nature of moving microsystem.

The precedence for on-board, monolithically fabricated diagnostics does not currently exist in the MEMS community. While this work is focused on the integration and demonstration of currently available technologies, it is also possible to monolithically fabricate accelerometer structures on chip for direct sensing. The authors envision fabrication schemes that allow for on-rotor vibration sensing with on-chip electronics for signal processing towards systems with integrated feedback.

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