Space Applications of MEMS: Inital Vacuum Test Results from the SwRI® Vacuum Microprobe Facility

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Abstract

We have designed and built the first fully functional vacuum microprobe test facility specifically intended to optimize the development of Micro Electro-Mechanical Systems (MEMS) devices for space applications. This facility includes an ion-pumped, ultra-clean vacuum system outfitted with four three-axis precision microprobe stages. The testing is monitored with a long focal length microscope through a thin sapphire window. Testing of several initial MEMS designs shows extremely promising results for using such devices in space applications. In particular, we show that significantly reduced voltages are adequate to resonantly drive some MEMS devices in vacuum owing to significantly reduced damping and the consequent much higher Qs of the systems (~1000x) in the absence of air. We also show the results of a many cycle ($>10^{10}$) test of a comb-driven, force-distance multiplied sliding aperture door and demonstrate that potential show-stopper issues such as stiction and vacuum welding can be overcome in MEMS devices properly designed for the vacuum environment.

Introduction

MEMS are an emerging technology, which promises to revolutionize many sensor and control systems applications. MEMS use micro fabrication technologies developed over the past several decades to build micro scale mechanical structures. Such structures can have many advantages over their macro scale counterparts including small mass and size, low power requirements, tight dimensional control, repeatability, potential for low cost with large production volumes, and very high reliability.

Because of the extremely high cost of launching instrumentation into orbit, the rigors of the launch and space environments, and the need for extremely high reliability devices, many of the advantages of MEMS technology are also well suited to space sensor and systems needs. Ultimately, space applications of MEMS could span the full range from science instrumentation to spacecraft engineering subsystems. Over the past several years, a number of groups have started to consider the use of MEMS for a variety of aerospace applications (e.g., see Table 1.2 in[1]). The majority of these applications have been in the aeronautics end of aerospace research. Among the concepts targeting space applications, most, such as magnetometers and gravity gradient monitors (nano-g accelerometers), can work in sealed and potentially shielded packaging that mitigates the concerns of open exposure to space.[2]

Space applications of MEMS have several unique issues. First, the launch environment produces very serious vibration and acoustic loads. Once in space, safe operation over thermal ranges of ~70°C are typically required and, depending on the orbit, lifetime radiation doses of >100 kRad along with deep dielectric charging and surface charging from the local plasma are not uncommon. Potentially more serious are the concerns for open packaged MEMS devices – those that have direct access to the vacuum of space. Such MEMS face the potentially fatal issues of stiction and vacuum welding between moving parts. Because the gas molecules in general, and low level humidity in air in particular, are thought to act as lubrication between moving parts, careful design and long duration, many cycle testing of MEMS held continuously in vacuum is essential.

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The vacuum environment is also considered an impediment for devices that require gas-dynamic damping because the higher Q (frequency of resonance/bandwidth of resonance) makes electronic feedback more difficult.[3] However, we believe that the reduced damping and higher Q in vacuum can be used to advantage in reducing required actuator voltages and thus power and power supply complexity. Because mass and power are tightly constrained in space applications, higher Qs and lower driving voltages could become a significant advantage for many such applications. Additionally, some applications such as RF filters and precision resonant frequency measurement are improved by higher Q devices.

MEMS for Space Applications

MEMS have begun to revolutionize sensor and control systems technology in the new millennium. Miniaturization of such functions is allowing the silicon revolution of the past several decades to extend and grow past the simple information handling of modern computing and into all aspects of our technology-driven lives. This is because the inputs (sensors) and outputs (controllers) are the bottlenecks that limit many everyday technology applications, particularly applications where dense nets of information or control are needed.

Since future satellite missions will be limited to small, low mass, low power consumption, and low cost instrumentation, instrumentation based around MEMS based technology are extremely attractive. MEMS devices are produced using the same techniques that have been developed by the semi-conductor industry to produce Integrated Circuits. Once the initial development of the fabrication process is completed, mass production of duplicate devices becomes very simple and inexpensive.

MEMS devices are intrinsically small and light. Typical minimum dimensions that are easily produced on MEMS devices today are approximately 1 μm. Despite their diminutive size, MEMS devices are surprisingly strong. The primary material used in the process, polysilicon, has an ultimate strength in tension that is nearly 4 times that of steel, but has about a third of the density. Tanner et al (2000) tested MEMS devices survivability to vibration loads. They tested their devices with a white noise spectrum with a frequency range from 20 to 2000 Hz with a power spectral density of 0.8 g/Hz, 40g RMS. At these high levels, they had 90% of tested devices pass and still function properly.

MEMS Vacuum Test Facility

We have designed and developed a vacuum microprobe test facility at the Southwest Research Institute (SwRI) specifically to enable the development, testing, and long term, in-vacuum, evaluation of MEMS devices for space applications[4]. To the best of our knowledge, the SwRI facility is unique in that it provides the full functionality of a flexible, well instrumented microprobe station within a high vacuum environment. The SwRI vacuum test facility, shown in Figure 1, has been developed to allow flexible and complete testing of MEMS devices while keeping them continuously within a high vacuum environment.

The centerpiece of this facility is our micro-manipulated vacuum microprobe station. Fitted to four of the ports are probes attached via movable bellows to x-y-z micrometer micro positioning stages. Stage motion is 5 μm per full turn in the lateral directions and 12 μm per turn in the vertical direction providing position control of the microprobes to <<1 μm. This fine manipulator control allows us to manually actuate the micromechanical devices if needed in addition to the basic function of providing input voltages to the various pads.

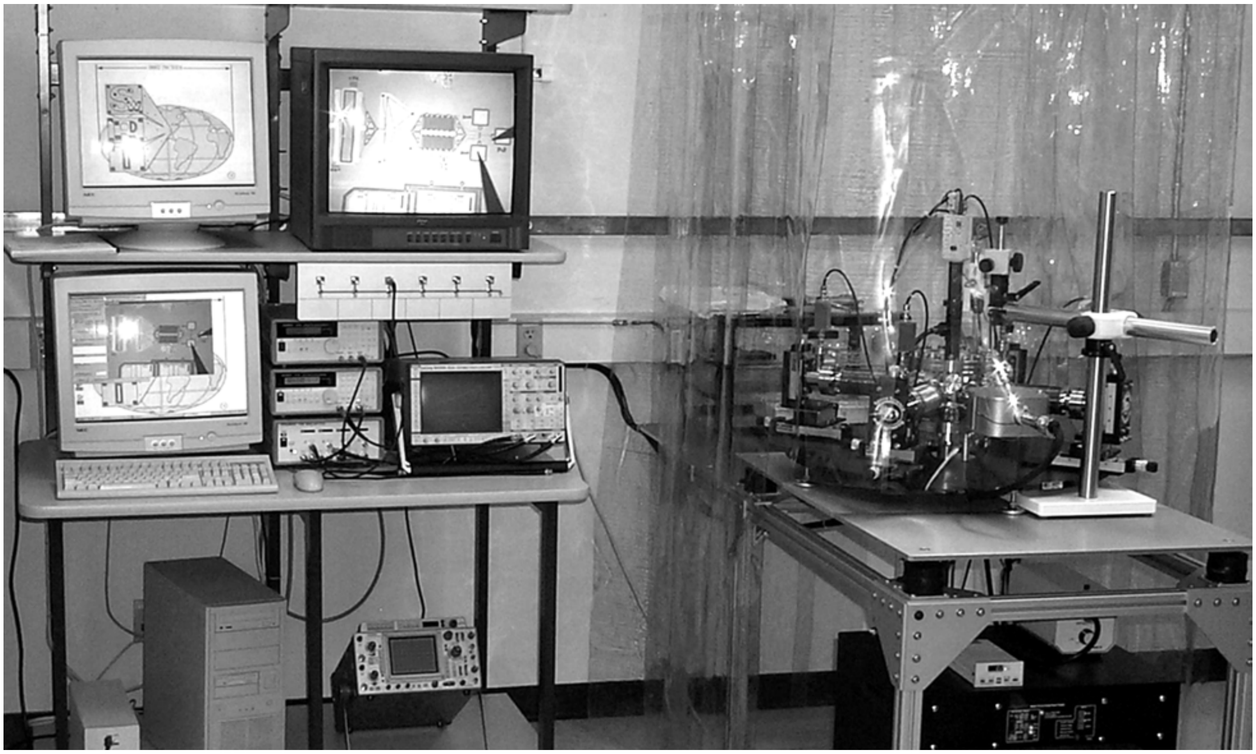

Figure 1. The SwRI MEMS development and test facility. The vacuum microprobe station, mounted on pneumatic dampers, and nitrogen-purged storage cabinet are inside the down flow clean tent while the control computer, ARBs, ARB signal amplifiers, and high resolution direct-feed monitor are on the adjacent workbench.

The station is contained within a HEPA-filtered, down flow environment, along with a nitrogen-purged cabinet where we store MEMS devices not presently in use. In this way, the MEMS chips can be removed from their transport containers and inserted into the vacuum microprobe station entirely within a clean environment. Continuous real-time imaging of the test devices is accomplished through a very thin (1.6 mm) single crystal sapphire window. Because of the large distance through the window and down to the test surface, we have developed an imaging system that incorporates one of two very long focal length primary objectives, followed by a CCD camera and image capture system. This provides coarse images that are ~1280 x 960 μm, with ~2 μm resolution and ~320 x 240 μm, with ~0.5 μm resolution, for coarse and fine imaging, respectively. A more thorough description of the facility is given in [4].

Initial Vacuum Testing and Results

These tests were set up to answer two fundamental questions about MEMS operation in vacuum. First, we sought to determine how important air damping is for the motion of MEMS devices. Second, we were very concerned that the air molecules in general, and the water vapor in the air, in particular were providing critical lubrication. Thus, it was important to determine if MEMS would work in vacuum at all. If they do function in vacuum, then it is critical to determine how their operational characteristics vary from those observed at atmospheric pressure and whether their functional lifetimes are adequate for typical applications.

We tested six separate size/type combinations of mechanical oscillators that are part of a materials test package developed at SwRI and fabricated using the Chronos MUMPS process.[6] These oscillators consist of a simply supported beam with a mass at the distal end. The edge of the mass supports comb-drive fingers for actuation. Figure 3 shows a photo of one of our medium-sized oscillator devices. When operated at resonance, the end mass oscillates with a large displacement. The devices were operated in the vacuum test chamber at various pressure levels using room air. At each pressure level, measurements were performed to determine the resonant frequency, the Q-factor, and the drive voltage required to achieve an end mass displacement of ±8 μm as measured by the blur envelope on the scale fabricated at the tip of the beam.

All six oscillator geometries were operated over the pressure range from 1 atmosphere to < 1.33 Pa (0.01 Torr). Results of this testing are summarized in Figure 4 (from [4]). For these tests, the system was started at atmospheric pressure and pumped down further between each set of measurements. The bottom panel of Figure 4 shows that the resonant frequency remains unchanged with pressure, as expected. In contrast, the required operating voltage decreases substantially at lower pressures from near 70 V at atmospheric pressure to less than 5 V at around 5 Pa (0.04 Torr). The Q-factor exhibits some interesting characteristics with pressure. As expected, the Q levels off at low pressures, however, this does not occur until ~13 Pa (0.1 Torr). Assuming that gas-dynamic damping would be the main damping force, we expected that almost all of the variation with pressure would occur above ~130 Pa (10 Torr), where almost 99% of the air has already been removed. Another surprise was the inflection in Q-factor at ~130 Pa (10 Torr), suggesting that some change in the physical mechanism of the damping process occurs around this pressure.

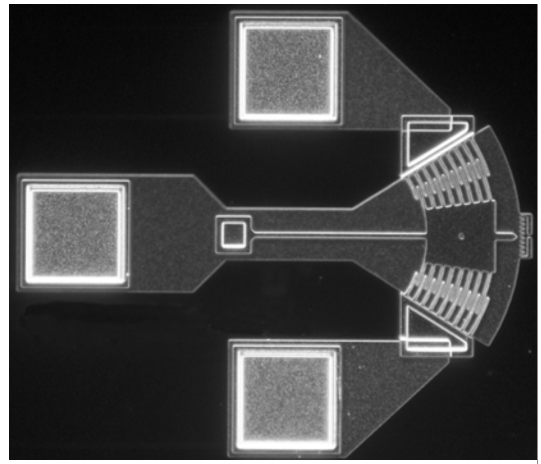

Figure 3. Photograph of a medium-sized type oscillator device.

Based on the results found in Figure 4, we decided to rerun this test with one device (P2S1) in order to determine if it mattered whether the MEMS were being further pumped down or let up in pressure (vented) between the measurements. Our thinking was that there might be some surface friction, owing to residual gas layers between the MEMS parts, in addition to the gas-dynamic damping. If so, we expected to see some hysteresis in the Q-factor as a function of partial pressure, with higher Q-values expected during times when the pressure was being let up compared to when it was being pumped down to a particular pressure level. Thus, we made our measurements in an increasing pressure regime after holding the MEMS parts under much lower pressure for an extended period. The increasing and decreasing pressure points coincided very well, showing no hysteresis.

Other interesting phenomena were observed on all devices tested at pressures below 13 Pa (0.1 Torr). The frequency response of a given device became asymmetrical, with the oscillation amplitude falling off much faster on the high frequency side of the resonance peak. Furthermore, very low damping leads to a slow ramp-up and ramp-down of the displacement amplitude when the drive signal is applied and removed. A device takes nearly a second to stabilize at maximum amplitude when turned on. Additionally, if the device was overdriven such that “pull-in” to the fixed comb fingers occurred, the device continued to resonate, merely bouncing off the fixed fingers. The low drive amplitude was not sufficient to short and hold the moving mass (as seen when overdriving normally at atmospheric pressure) until the drive voltage amplitude was increased to ~15 volts. This feature could be important for space applications of MEMS as it is harder to get the devices to lock up at the lower driving voltages, making them more robust.

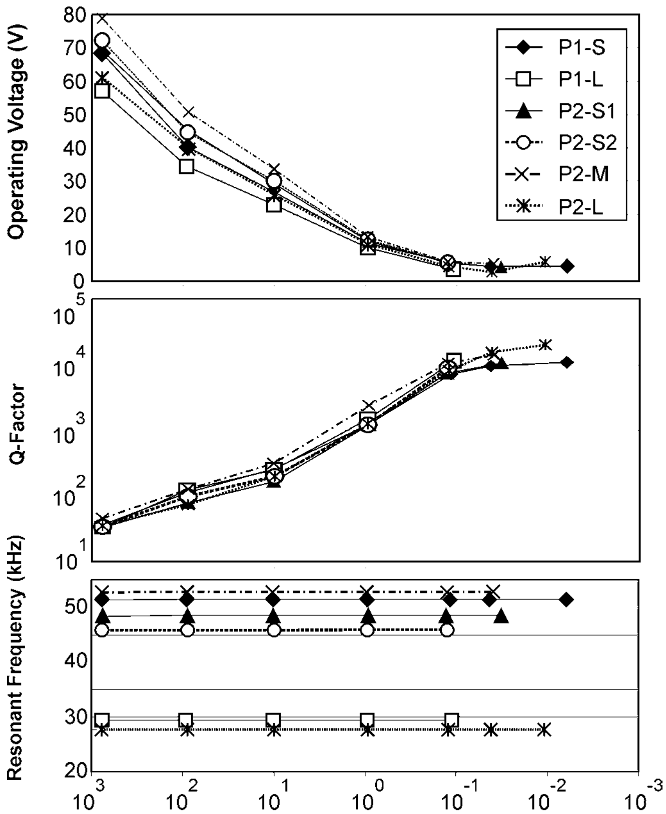

Figure 4. Required operating voltage, device Q-factor, and resonant frequency plotted versus partial pressure of air in the microprobe station. All six oscillator geometries show the same basic response, with full vacuum-type motions not being experienced until the pressure is below ~13 Pa (0.1 Torr).

In order to assess the survivability of MEMS devices over numerous cycles in vacuum, we set up a test of the large sliding door device. The device comprises a fringing field driven comb drive coupled to a force-distance multiplier,[7] and then to 40x446 μm sliding door. This device was built using the Sandia National Laboratory SUMMiT process [http://mems.sandia.gov/scripts/index.asp] and made use of several standard parts from their design catalog.

We ran the door over a range of motion of ~20 μm using a simple sinusoidal driver. While this waveform is not optimized for the mechanical structure, frequencies up to 10 kHz were possible without abnormal motions. Because we ran the structure outside of its resonance, the peak driving voltage was relatively high (~100V). The test took place over several weeks of continuous vacuum exposure with several short intervals of oscillation during our set up process. We also exposed this device to over-voltage conditions on several occasions and had to mechanically return the structure to its nominal position using one of the microprobes. Thus, this process constituted a severe over-test of the structure compared to the sort of handling that would be done on space flight parts.

Once the driving voltages and frequency had been worked out manually, we began the long duration testing under the computer control. A total of >287 hours total running time was collected at 10 kHz, producing $>10^{10}$ cycles on the entire mechanism. Throughout this time, the blur image was periodically monitored, and no obvious change in the motion was observed. At the end of the test, slow (1-10 Hz) cycling of the door was performed; this motion did not indicate any change compared to the pre-test motion.

Discussion

We have constructed the first vacuum microprobe test facility intended specifically for the development of MEMS devices for in-space applications. This extremely flexible and highly integrated facility allows us to optimize the development of MEMS for the rigors of the space environment. Further, initial in-vacuum testing has shown extremely promising results, indicating that MEMS will likely be suitable for numerous applications in various space sensors and control systems.

In addition to indicating that MEMS are suitable for space applications, these results suggest that many MEMS devices used in sealed packages for terrestrial applications might benefit from vacuum packaging instead. Vacuum packaging will significantly enhance the Q of various oscillators, improving their performance for applications such as RF filters and precision resonant frequency devices. Comparison of performance in air and that in vacuum indicates that the Q of the device was ~1000 times greater in vacuum. While some improvement in the motion was expected, this very large difference was not anticipated. In addition, the results shown in this study indicate that the damping process observed at various partial pressures does not appear to be due to simple gas-dynamic damping alone. Rather, a more complicated and interesting set of physical mechanisms appears to be at work.

Thus, we have demonstrated that MEMS devices can function for many (>10^{10}) cycles in vacuum and that their motion is actually improved, requiring less voltage, in some applications. We have designed, built, and tested the first fully functional vacuum microprobe test facility specifically intended to optimize the development of MEMS devices for space applications and have embarked on the adventure of developing and ultimately flying MEMS-based scientific instruments and spacecraft systems on future space missions.

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