OPTICAL MEMS-BASED SEISMOMETER

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ABSTRACT

Low-yield man-made seismic activity is difficult to detect and most often occurs in remote areas where seismic detection is weak. The Whispering Gallery mode based Seismometer, "WhiGS", is an optical Micro-Electro-Mechanical System-based (MEMS) instrument. The seismometer is a three-axis instrument, is compact, has low power consumption and is capable of unattended operation.

WhiGS exploits morphology-dependent optical resonance shifts in small dielectric spheres (<1 mm in diameter). These optical resonances, called whispering gallery modes (WGM), are extremely narrow, making the transducer highly sensitive to force (< 10^{-9} Newtons). The MEMS sensing element in this seismometer has demonstrated an optical Q-factor of 10^7. As a result, the instrument is capable of measuring accelerations as low as 10 nano-g.

The prototype design is completed. The mechanical fabrication of the prototype is ninety percent (90%) complete. Preliminary tests of the instrument have been conducted and results are presented in this paper.

OBJECTIVES

Michigan Aerospace Corporation, in collaboration with Southern Methodist University, is developing a compact Whispering Gallery Seismometer (WhiGS). The sensing principle of the seismometer exploits the morphology-dependent optical resonance shifts of dielectric spheres to detect ground motion. These optical resonances are extremely narrow, making the transducer highly sensitive to ground motion. The small dielectric spheres are easily packaged into a small instrument capable of measuring accelerations as low as 10 nano-g.

The optical MEMS sensing element, typically a microsphere (with diameters in the range 200 to 1000 μm), is weakly coupled to an optical fiber, as shown in Figure 1a. The optical fiber, which carries light from a tunable laser, serves as an input/output port for the microsphere. When the microsphere comes into contact with an exposed section of the fiber core, light is coupled into the outer layer of the sphere, (Figure 1b). Its resonances are observed as sharp dips in the transmission spectrum as depicted in Figure 1d. When the sphere is compressed (as shown in Figure 1c), the wavelength of the resonances shifts.

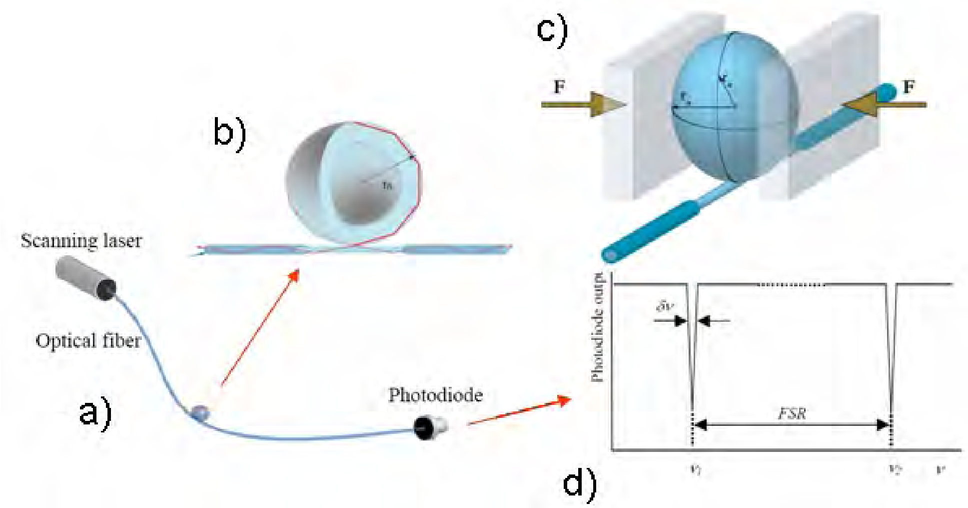

Figure 1. Principle of the WGM pressure-induced wavelength shift $\delta\nu$.

These optical resonances, also known as the "whispering gallery modes" (WGM), are extremely narrow and hence are highly sensitive to any morphological change in the microsphere.

The Phase II objectives include the fabrication of the dielectric microspheres, engineering model fabrication and preliminary tests, and instrument fabrication.

Objective 1
The first objective of this effort was the experimental investigation of WGM characteristics of different-sized spheres (ranging from ~ 200 μm and 1 mm) and the fabrication of the microspheres. The candidate material used for the spheres is PDMS (commercially known as Sylgard 184).

Objective 2
The second objective was the fabrication of the engineering model to demonstrate the seismometer principle.

Objective 3
The third objective entails the fabrication of the seismometer prototype.

RESEARCH ACCOMPLISHED

The transducer uses morphology-dependent optical resonances described by Benner and Hill (1988), whispering gallery modes (WGMs) in this case, investigated by Guan et al. (2006), to measure minute shape variations in dielectric spheres squeezed between the mass and the instrument base. The dependence of the wavelength on the force is expressed as

$$\delta F = \frac{\lambda}{Q}\left(\frac{d\lambda}{dF}\right)^{-1}$$

where Q is the quality factor. The table below shows change of wavelength with force applied (dλ/dF) and the force resolution for several different sphere materials and dimensions. Polymer base-to-cure agent ratios of up to 60:1 were used in this investigation ($\frac{d\lambda}{dF} = 181 pm/\mu N$, ***Table 1***)Table 1 lists the optimal characteristics for damping and sensitivity.

Table 1. Parameters for the mechanical design

Parameters	
Mass (kg)	0.01
Stiffness (N/m)	631
Resistance Constant (kg/s)	0.5
Sphere: PDMS	181 pm/μN
Q Factor (Mechanical)	5
Decay Modulus (s)	0.04

Our goal at the onset of the program was to demonstrate the validity of the proposed concept using a bench test. To do so, a spring-proof mass assembly was designed, fabricated and tested to verify that

- the bandwidth extends over 40 Hz,
- the spring is compliant enough to compress the sensing elements, i.e., the polymer microspheres, and
- the spheres register noticeable wavelength shifts at nano-g's acceleration.

The conceptual design of one axis of the seismometer is shown in Figure 2. The opto-mechanical assembly of the seismometer is composed of the spring-proof mass assembly and a polymer microsphere positioned between the proof mass and the seismometer base and an optical fiber to couple infrared light into the equatorial region of the microsphere. As the proof mass is set in motion by ground motion, the proof mass compresses a polymer microsphere. The morphological deformation of the microsphere under compression shifts the naturally occurring optical resonances in the sphere, proportionally to the physical deformation. The Q-factor of these optical resonances is ~10^7 thus providing the ability to detect acceleration as small as 10 nano-g.

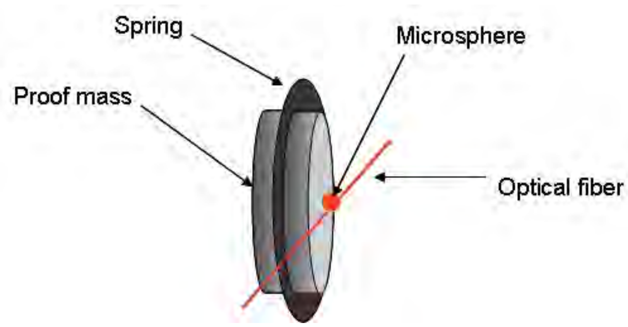

Figure 2. Whispering gallery mode based seismometer principle.

Prototype Design and Fabrication

The seismometer prototype was designed and fabrication is 90% complete. Figure 3 shows the prototype assembly containing the electronics and batteries, positioned in the upper level of the prototype. The opto-electronics are located in a bottom tray. The two trays are separable for inspection and easy access to components. The sensing elements for the seismometer ("pucks") are also positioned in the bottom tray.

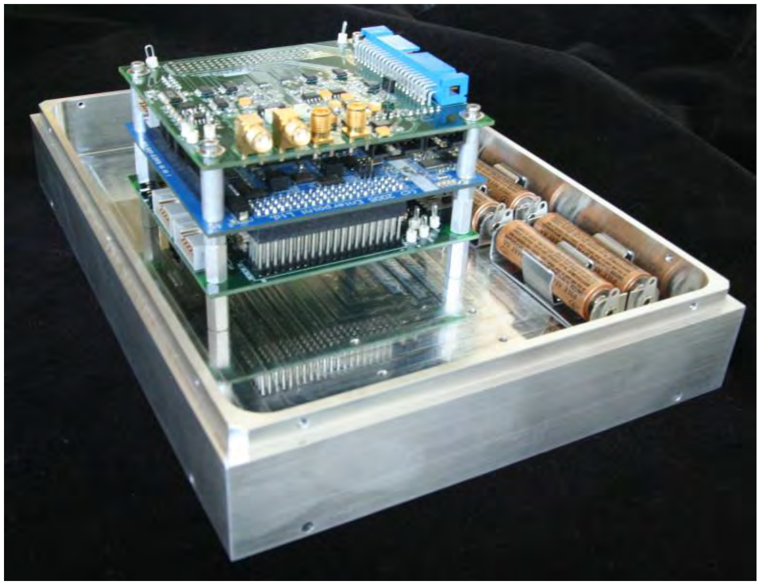

Figure 3. Prototype electronics assembly (top tray).

The field version of this prototype will be equipped with application-specific integrated circuit electronics and therefore will be significantly more compact. The large scale of this prototype allows for easy modifications and debugging.

Figure 4 shows an opened housing, "pucks" for the sensing element (fiber and microsphere), and the proof mass and spring. The spring is located under the proof mass.

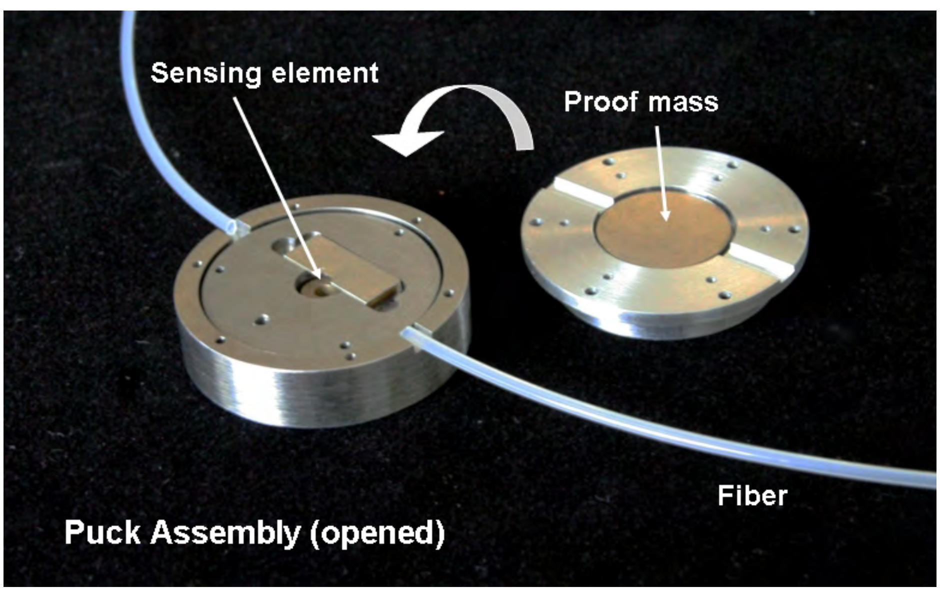

Figure 4. Seismometer (puck) components designed to hold the sensing element.

Electronics
The development of the electronics entails the programming of a field programmable gate array (FPGA) to digitize the output of the photodiode detector and track the resonance shifts caused by the deformation of the polymer microspheres under compression. The laser, laser driver and controller, fibers and photodiode detectors were assembled to characterize the sensing element performance and operating characteristics.

The role of the processing electronics consists of identifying an optical resonance in the microsphere and tracking the wavelength shift of that resonance caused by the microsphere deformation, as shown in Figure 5. The processor instructs the driver controller to scan the current of the laser, and therefore the wavelength. The processor selects a resonance (dip in the detector output), and then instructs the driver controller to scan around the resonance. Once the processor is “locked” around a resonance, the current is dithered around that value.

All the components have been selected based on pin count and power dissipation. An analog-to-digital converter will be sampling the waveform detected from the photodiode. Parts were readily available with our constraints which dissipate roughly 3-5mW of power. The analog-to-digital converter is a serially-operated device to conserve the number of pins required for it to operate. Examples of such devices would be the AD7694 or the AD7685. An FPGA was selected for this application (ACTEL Igloo Series). Assuming a 1-MHz internal clock rate and complexity similar to some of our other designs, the Igloo FPGA is expected to consume no more than 5mW of power. If for some reason the clock rate had to be increased to 5 MHz, the estimated power consumption would increase to about 15 mW.

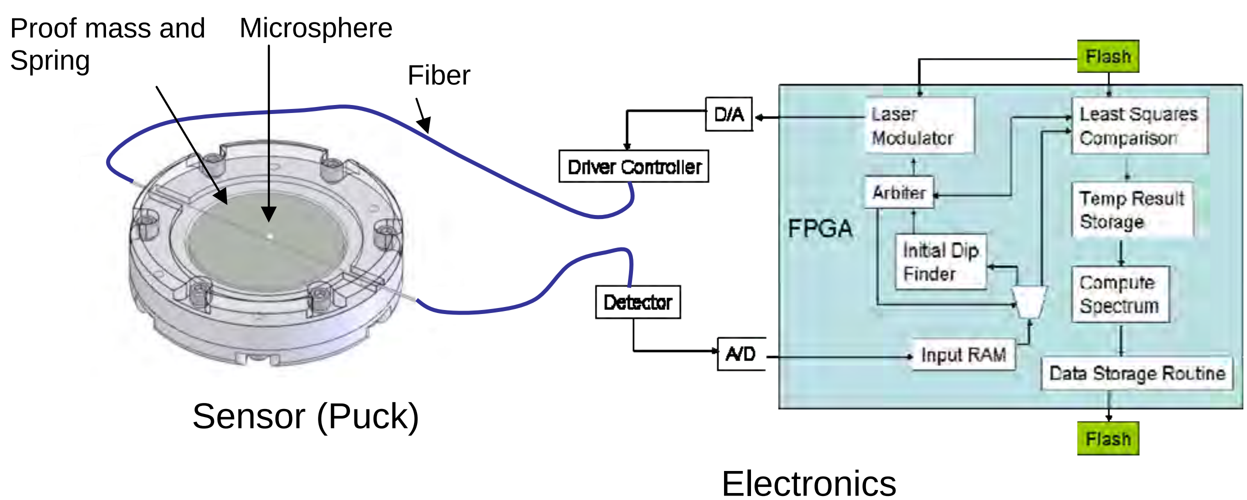

Figure 5. Functional diagram for the sensing element.

Figure 6 displays a photograph of the populated electronics boards. The power supply board (left) supplies the power from the batteries to the optoelectronics and the analog interface board. The analog interface board controls the laser from the PD output, and the seismometer output.

Figure 6. Photograph of the electronics boards, power supply board (left) and analog interface board (right).

Test Results

Results on a preliminary data set were obtained with the breadboard model and the processing algorithms were developed. A second order polynomial was determined to be a good interpolation to locate the minimum (to track the resonance shifts); the processing time is short enough to track the resonance in real time and the interpolation provides good accuracy for the shift determination.

A fixed-width sub-scan (dithering) is used to more finely sample the peaks. From there, two different methods are currently used to track the peaks:

- “Simple Method”: Record the sample that corresponds to the highest point in the peak, along with the samples that correspond to the 1/3 height, 1/2 height, and 3/4 height of the peak and average them all together to get the “center” of the peak.
- “2-order Poly”: Use the peak value from the previous dataset as a starting point, record of a subset of samples around the peak for use in a 2-degree polynomial least-squares fit. Using the result of the least-squares fit, directly solve for the peak of the curve. An example of the processing is shown in Figure 7.

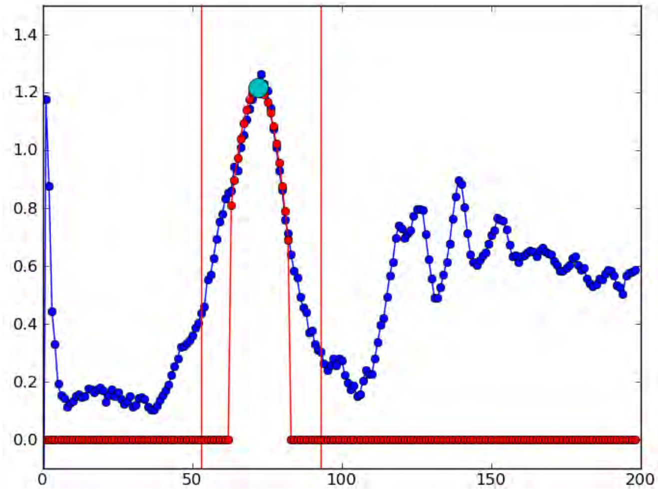

Figure 7. The 2-order polynomial fit on a resonance peak (Note: The polarity of the signal has been flipped in the plot, as resonances are associated with a drop in the light transmission).

Using a 2-order poly requires that only 9 values be stored for the least-squared matrix processing. Other values are based on the incoming samples directly, thus alleviating the need to store large amount of data.

Figure 8 shows acceleration measurements obtained with a PMMA microsphere on the test bench. An accelerometer was used to track the acceleration on the shake table. The frequency response of the accelerometer is lower than that of the seismometer. As a result, the accelerometer doesn't resolve some of the frequencies as seen in Figure 8. These experiments were conducted with PMMA spheres which are less sensitive then PDMS however, simpler to use during the development phase. PDMS spheres will be used for the final prototype.

Higher order polynomials can be used at the expense of not being able to directly solve for the peaks. In those cases, there would need to be additional iterations though sub-samples to find the maximum peak value. Resources are very limited in low-power FPGAs.

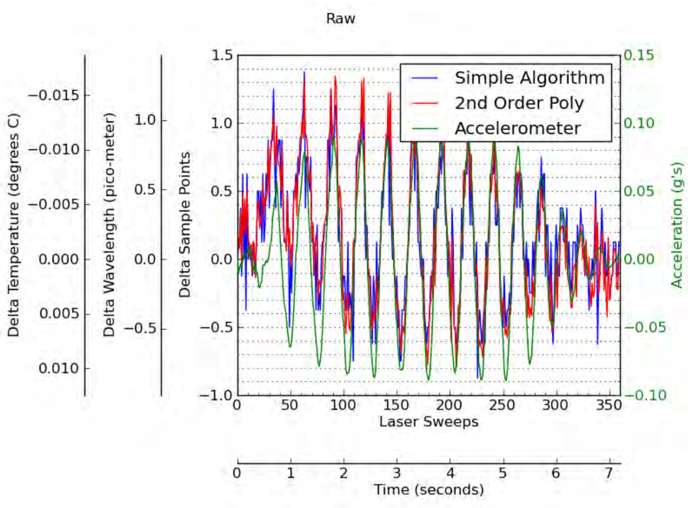

Figure 8. Acceleration measurements using resonance tracking. An accelerometer was placed on the shake table for comparison.

CONCLUSIONS AND RECOMMENDATION

Bench tests have demonstrated that optical resonances can be successfully used to track acceleration. Simple processing, doable using an FPGA, is sufficient to determine and track the location of the resonances.

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