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 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 will be capable of measuring accelerations as low as 10 nano-g.

The design and demonstration of the sensing element performance were completed in Phase I. Hollow dielectric microspheres, core of the sensing element, were capable of detecting nano-Newton forces. As a result, the proof mass weighs less than 10g per axis and the volume of the instrument is less than 5 cubic inches (< 80 cm^3). The on-board processor and electronics dissipate less than 160 mW per channel. This Phase II effort entails the final design, fabrication and testing of the deployable 3-axis seismometer.

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 Phase I objectives included the characterization of whispering gallery mode shifts in microspheres as force sensor, preliminary tests, and instrument design.

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.

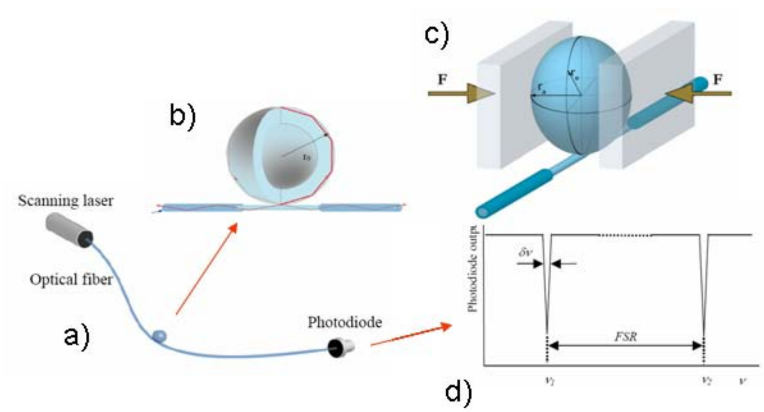

Figure 1: Principle of the WGM pressure-induced wavelength shift $\delta\nu$.

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. Other micro-resonator geometries, such as micro-discs, can be used as sensing elements in place of the microspheres.

The first objective of the Phase I effort was a computational and analytical analysis to determine the range of force/acceleration sensitivities and ranges for the sphere sizes and materials to be used in our sensor. For this, the analytical approach and finite element analysis (FEA) tools developed in our previous study will be used. These FEA tools are described in Nguyen et al. (2009). This objective entails the quantification of the precise effect of force and microsphere physical deformation on electromagnetic wave propagation in microspheres with the selected sizes and sphere material.

The second objective of this effort was the experimental investigation of WGM characteristics of different-sized spheres (ranging from ~ 200 μm and 1 mm). The candidate material to be used for the spheres is PDMS (commercially known as Sylgard 184). Different percentage of additives (cure agent) will be used to obtain different elastic modulus values and optical characteristics in order to determine the force sensitivity ranges that can be achieved and their suitability for the seismometer to be developed. Polymer base-to-cure agent ratios of up to 60:1 were used in this investigation.

The third objective of the Phase I effort was the design of a seismometer prototype. That included the design of the transducers and the mechanical design of the instrument. The design of the instrument entailed the following considerations:

- Determination of the inertial mass and shape
- Sensitivity
- Resonant frequency
- Ability to measure 3 axes
- Damping mechanism to prevent long-term oscillations
- Electronics circuitry and noise

RESEARCH ACCOMPLISHED

Force Measurements Using WGMs in Spheres

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. Force resolution of $1x10^{-4}$ N was achieved using polymer spheres, and to $1x10^{-6}$ using hollow polymethyl methacrylate (PMMA) spheres, shown by Kozhevnikov et al. (2006) and Ioppolo et al. (2007). Current studies by the same team using 0.7 mm spheres of another polymer, polydimethylsiloxane (PDMS), indicate that a force resolution of 10^{-8} N is possibly exploiting the same sensing principle.

The dependence of the wavelength on the force is expressed as:

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

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.

Table 1: Comparison of force sensitivity and resolution for spheres of various materials with comparable diameter (910±50 mm). The sensitivity of PDMS spheres depends on the volumetric ratio of polymer to hardening material. In the present case, the ratio is 60:1.

Material	dλ/dF, pm/μN	Resolution, N
Hollow PDMS (60:1)	50,000	2×10^{-12}
Solid PDMS (60:1)	181.2	$7x10^{-10}$
Solid PDMS (20:1)	3.2	$4x10^{-8}$
Solid PnHMA	$86x10^{-3}$	$1.5x10^{-6}$
Hollow PMMA	$76x10^{-4}$	$1.7x10^{-5}$
Solid PMMA	$1.8x10^{-4}$	$7x10^{-4}$
Solid Silica	7.5×10^{-6}	$1.7x10^{-2}$

The model developed as part of this effort was compared to experimental results using PDMS spheres (Ioppolo et al. 2009), as shown in Figure 2. Good agreement is shown between the experimental and analytical data.

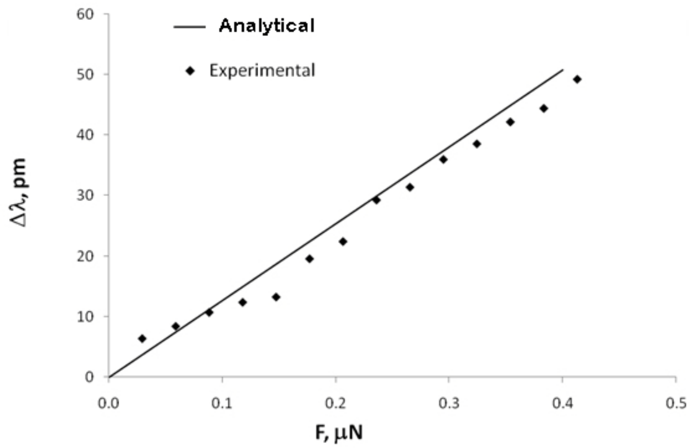

Figure 2 Analytical and experimental sensitivity results of a solid PDMS (50:1) sphere (D=910 mm)

Seismometer Design

The overall design of the seismometer is shown in Figure 3. The acceleration sensing elements are contained in the sealed canisters (3-Axis Sensing). The electronics and battery pack are compact and low dissipation. The overall package occupies less than 80 cm^3.

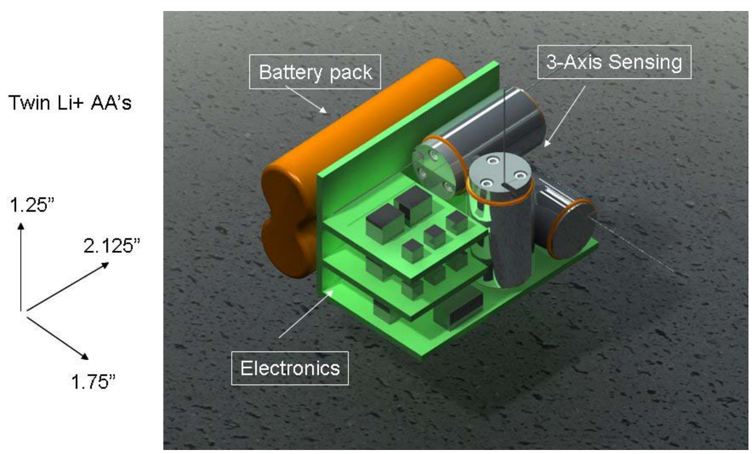

Figure 3: Seismometer design. The sensing apparatus is contained in the sealed cylinders

A model of the seismometer was developed to determine the characteristics of the principal components (mass, spring and sensing element). Table 2 lists the optimal characteristics for damping and sensitivity and Table 3 lists the electrical requirements of the seismometer.

Table 2: 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

Figure 4 and Figure 5 both show the SolidWorks™ model of one of the two horizontal axes of the seismometer. The proof mass is mounted off-axis on a jewel bearing. The microsphere is mounted closer to the axis, using the cantilever ratio to amplify the force transmitted to the microsphere, as shown in Figure 5 and Figure 6. The spring is mounted onto the axis.

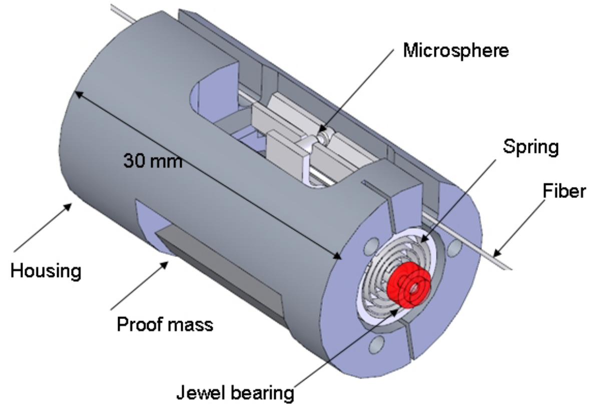

Figure 4: SolidWorks design of the instrument

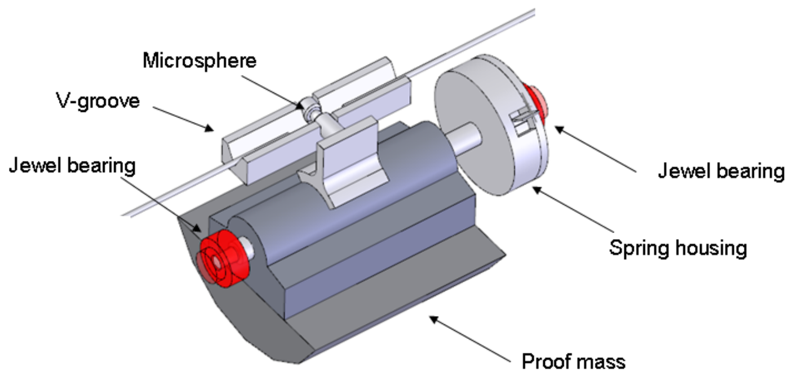

Figure 5 View of the seismometer without the housing

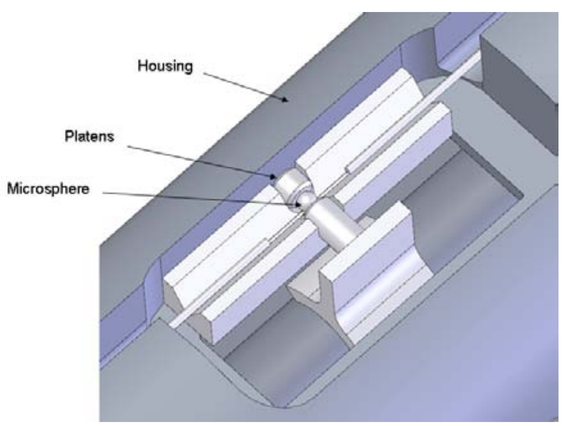

Figure 6: Microsphere positioning

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 7. 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.

Space conservation is paramount in the design of this small seismometer. The easiest way to conserve space is to reduce the number of pins and traces required for the circuit. 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 are readily available with our constraints which dissipate roughly 3-5mW of power. The analog-to-digital converter would ideally be 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. A Field Programmable Gate Array (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.

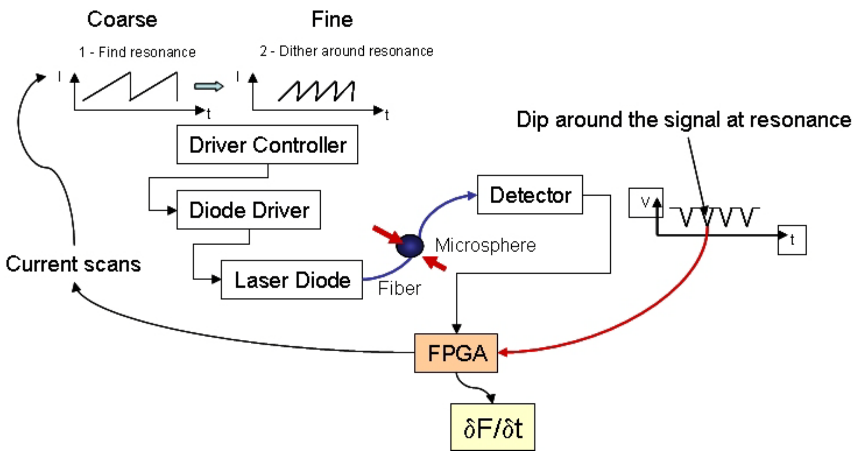

Figure 7: Functional diagram for the sensing element

Table 3: Electrical characteristics of the seismometer

Component	Dissipation (mW)
Laser Diode Controller	45
TEC Controller	100
Processor	15
Total	160

CONCLUSIONS AND RECOMMENDATION

The sensitivity of the sensing element was demonstrated and the design of the seismometer was completed in Phase I. The design will serve as a baseline for the Phase II effort. During the Phase II, a seismometer prototype will be fabricated and tested. Specific attention will be given to the critical components such as the mounting of the microspheres and the mechanical assembly.

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REFERENCES

Benner, R.E.and S. C Hill (1988). Morphology-dependent Resonances, in *Optical effects Associated with Small Particles*, P.W. Barber and R.K. Chang, Eds., *Advanced Series in Applied Physics*, World Scientific.

Guan, G., S. Arnold and M.V. Ötügen, (2006). Temperature Measurements Using a Micro-Optical Sensor Based on Whispering Gallery Modes, *AIAA Journal* 44: 10, 2385–2389.

Ioppolo, T., M. Kozhevnikov, M.V. Ötügen, and V. Sheverev (2007). Performance of a whispering gallery mode resonator-based micro-optical force sensor, Paper 2007-1262, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV.

Ioppolo, T., U. K. Ayaz, U.K., and M.V. Ötügen (2009). High-resolution whispering gallery mode force micro-sensor based on polymeric spheres, Paper 2009-1450, 47th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, FL.

Kozhevnikov, M., T. Ioppolo, V. Stepaniuk, V. Sheverev, and V. Ötügen (2006). Optical force sensor based on whispering gallery mode resonators, Paper 2006-649, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV.

Nguyen N., N. Gupta, T. Ioppolo, and V. Ötügen (2009). Whispering Gallery Mode-Based Micro-Optical Sensors for Structural Health Monitoring of Composite Materials, *J. Mat. Sci* 44: 1560–1571.