OPTICAL MEMS-BASED SEISMOMETER ”WHIGS”

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Sponsored by National Nuclear Security Administration

Contract No. DE-FG02-08ER85099

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 a Q-factor of 10^7. As a result, the instrument will be capable of measuring accelerations as low as 10 nano-g.

This Phase I SBIR effort entails the development of the MEMS sensing elements and the complete design of a deployable 3-axis seismometer.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Optical MEMS-Based Seismometer 'Whigs'**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Michigan Aerospace Corporation,1777 Highland Drive, Suite B,Ann Arbor,MI,48108**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 30th Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies, 23-25 Sep 2008, Portsmouth, VA sponsored by the National Nuclear Security Administration (NNSA) and the Air Force Research Laboratory (AFRL)

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

OBJECTIVES

Michigan Aerospace Corporation, in collaboration with Southern Methodist University, is developing a compact WhiGs for monitoring man-made seismic activity. 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.

In a typical seismometer the transducer element measures the relative displacement between the mass and the ground. The position of the mass relative to the ground is maintained, and a damper is used to minimize resonance. The transducer can be chosen to measure either relative mass displacement using a lever assembly or voltage output from a bridge, or relative mass velocity using magnetic induction. In the latter case, slow ground motion is difficult to detect as the induction is proportional to the relative mass velocity.

The present effort proposes to use a resonant micro-optical element as a transducer. 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. Recent studies at Southern Methodist University have shown that force resolutions of 5×10^{-3} N could be obtained by measuring WGM shifts in silica spheres. This resolution was improved to 1×10^{-4} N using polymer spheres, and to 1×10^{-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 possible by exploiting the same sensing principle.

The Sensing Element

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 in Figure 1c), the wavelength of the resonances shifts.

These optical resonances—the WGMs—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.

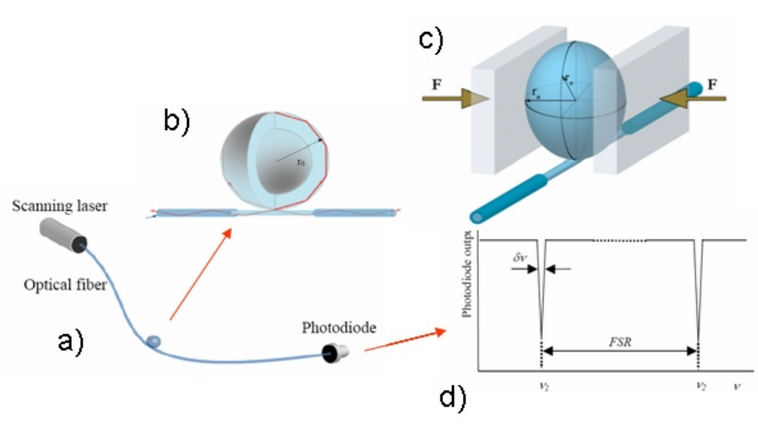

Figure 1. Principle of the WGM pressure-induced wavelength shift $\delta\nu$.

Task 1: Whispering Gallery Mode Shifts in Spheres as Force Sensor

The first task is 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. (2007). 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.

Task 2: Preliminary Tests

The WGM characteristics of different-sized spheres (ranging from ~ 200 μm and 1 mm) will be investigated. The candidate material to be used for the spheres is PDMS (commercially known as Sylgard 184). Different percentages of additives (cure agents) 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 50:1, 20:1 and 10:1 will be used at the first stage. The WGMs of the spheres will be interrogated using a distributed feedback diode laser with nominal wavelength in the infrared (~1.3 μm). The spheres will be calibrated in a vacuum chamber with a micro-cantilever beam force inducer. The deflection of the cantilever beam will be monitored using a Michelson interferometer setup. The vacuum chamber eliminates unwanted/uncontrollable aerodynamic forces that can affect the calibration process at such low force levels (in the order of nanonewtons). The effect of sphere size and additive ratio on the Q factors will also be investigated and methodologies to obtain higher Q values will be sought (beyond the currently achievable $Q \approx 10^7$). A small number of high-Q spheres will be produced to be used in the prototype seismometer.

Task 3: Instrument Design

The third task of this effort will be the design of a seismometer prototype. This will include the design of the transducers and the mechanical design of the instrument. The design of the instrument will include the following considerations:

- The determination of the inertial mass and shape
- The sensitivity
- Resonant frequency
- The ability to measure 3 axes
- A damping mechanism to prevent long-term oscillations
- Electronics circuitry and noise

Figure 2 shows a schematic of the 3-axis seismometer. Each cylinder contains a suspended proof mass and one sensing element.

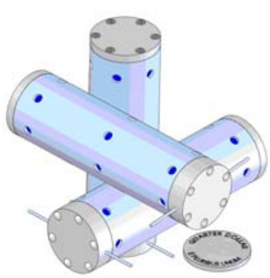

Figure 2. Schematic of the 3-axis seismometer (a quarter is shown for reference).

RESEARCH ACCOMPLISHED

Support for this work was recently awarded and the research accomplished is in its early phase. The results presented in this section were obtained to establish the capabilities of such design.

Force Measurements Using WGMs in Spheres

Figure 3 shows the resonant shift variation when a solid PMMA sphere (Figure 3a) and a hollow sphere (Figure 3b) are subjected to a measured force. In Figure 3a), the decompression measurement was conducted five days after the compression measurement. The dependence of λ on force is linear and shows no hysteresis. During the period between the two measurements, the sensor was left compressed at the maximum force indicated in the figure. No degradation was observed. Hollow PMMA spheres exhibit a significantly higher sensitivity, and the sensitivity is dependent on the wall thickness.

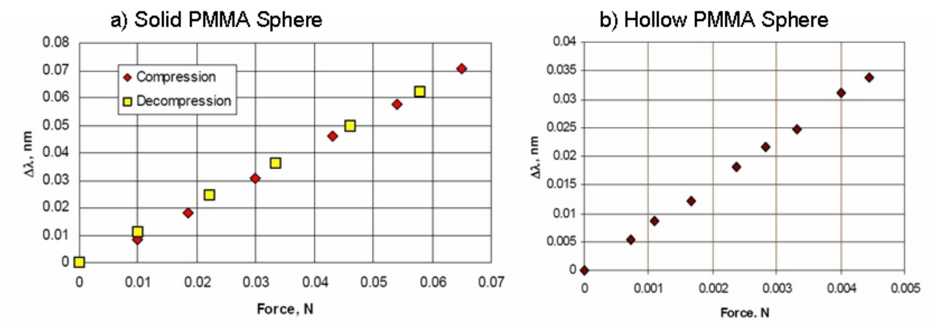

Figure 3 Resonant shift variation with force: a) solid PMMA, (diameter D = 470 μm) and b) hollow PMMA sphere (diameter D = 960 μm).

Preliminary Design

Figure 4 shows a functional diagram of the sensing element used as a transducer. Light from a diode laser is coupled into a waveguide (optical fiber) which serves as the input/output conduit. Some of this light, in turn, is coupled into a polymer sphere placed on the waveguide. The laser frequency is scanned (dithered) in a very narrow bandwidth. The transmission spectrum is monitored at the output of the waveguide using a photodiode. The photodiode output, in turn, is fed into a proportional-integral-derivative (PID) controller that provides feedback into the diode laser and locks the laser wavelength to a given optical resonance (WGM) of the sphere. The laser current (which is proportional to its wavelength) is monitored externally, which provides the necessary information on the WGM shift. The feedback system allows for the monitoring of fast shifts in the WGM with a bandwidth limited by the dither frequency bandwidth of the laser (several tens of kHz). The output signal from the laser is transmitted to a remote receiver for further analysis.

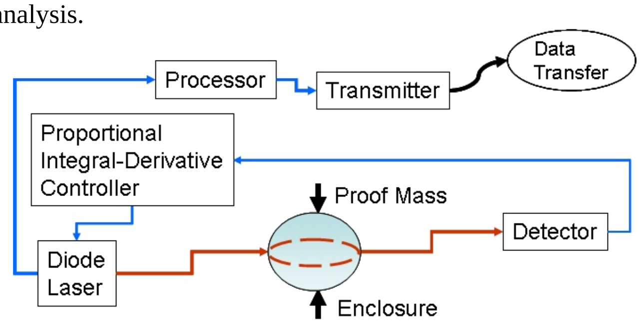

Figure 4. Functional diagram for the sensing element.

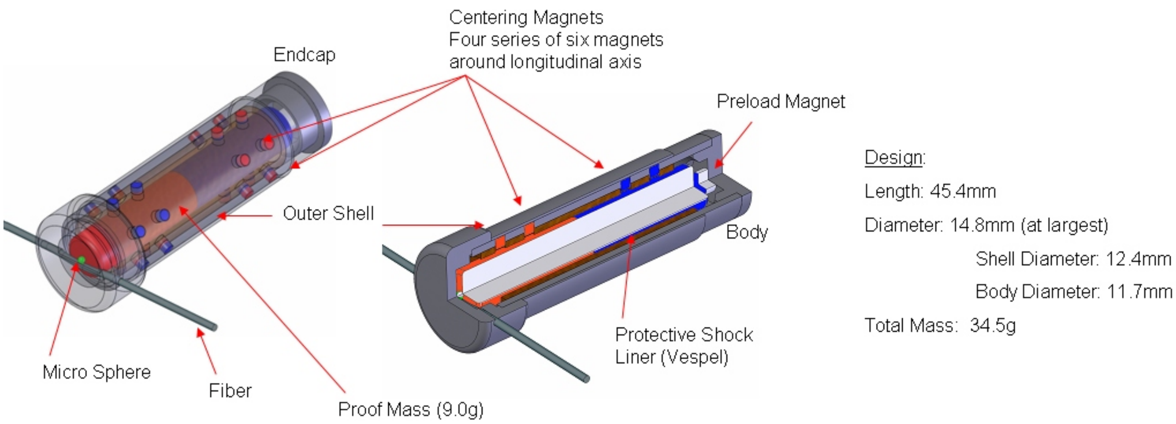

Figure 5. Conceptual design of one arm of the seismometer.

The baseline design for the each orthogonal horizontal axis is shown in Figure 5. The proof mass is suspended with magnets, and a preload magnet maintains the mass against the micro-sphere. The total mass for one arm of the instrument is less than 35 grams.

Other designs are being considered as part of a trade study.

CONCLUSIONS AND RECOMMENDATION

The design and development of the seismometer are under way. Preliminary tests indicate that the high Q-factor of the whispering gallery modes enable a seismometer sensitivity in the nano-g range. Once the optimal mechanical design is selected, analytical work, modeling, and electronics design will be conducted to determine the seismometer characteristics.

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