AN ACCELEROMETER DESIGNED TO INVESTIGATE THE EFFECTS OF GRAVITY SHIELDING

Richard R. Gauthier
Consortium for Holography, Applied Mech. & Photonics
University of Alabama in Huntsville
Huntsville, Alabama 35899

John A. Gilbert
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
Huntsville, Alabama 35899

Ning Li
Superconductor & Gravity Laboratory
University of Alabama in Huntsville
Huntsville, Alabama 35899

ABSTRACT

This paper describes a new device, called a *Transversely Suspended Accelerometer (TSA)*, designed to measure acceleration at low frequency with high sensitivity in the vicinity of a strong magnetic field. The TSA is a simple diffraction-limited image positioning device capable of measuring constant (DC) and variable (AC) acceleration simultaneously in two perpendicular directions. It has a resonant frequency of 5.2 Hz (33 rad/s), a range of 0 to 20 mG's, a sensitivity of 25 µG's, and a spatial resolution better than one measurement per four cubic millimeters.[1] Steps taken to design, calibrate, and test the TSA are described, and a brief description of one potential application for using the device as a gravitometer is presented.

INTRODUCTION

Several years ago, the possibility of a new phenomenon called gravitational shielding (GS) was reported by Podkletnov and Nieminen [1]. They claimed that material objects placed above a superconducting apparatus experienced a decrease in weight on the order of one percent the normal weight. The phenomenon was observed while spinning a large superconducting disk using high frequency magnetic fields. The disk, cooled to a temperature below 77 °K, levitated in a static magnetic field according to the Meissner effect.

Although theoretical work [2] has been published to suggest a possible mechanism for GS, only limited efforts have been made to obtain a precise knowledge of the experimental conditions under which the phenomenon is observed. In Podkletnov and Nieminen's experiment, for example, it would have been useful to measure the spatial dependence of the effect in a plane above the disk, the vertical positional dependence, the directional dependence (including a possible effect at the sides of the disk), etc. A suitably designed gravitometer could help to obtain this information.

This paper describes a new device, called a *Transversely Suspended Accelerometer (TSA)*, designed to act as a gravitometer in the vicinity of the high magnetic fields associated with GS. The TSA is a simple diffraction-limited image positioning device capable of measuring constant (DC) and variable (AC) acceleration simultaneously in two perpendicular directions. It has a resonant frequency of 5.2 Hz (33 rad/s), a range of 0 to 20 mG's, a sensitivity of 25 µG's, and a spatial resolution better than one measurement per four cubic millimeters.

THE TRANSVERSELY SUSPENDED ACCELEROMETER

An accelerometer is rigorously defined as an instrument used to measure the acceleration of a moving object. When such a device is used to measure a change in the gravitational field relative to a stationary position, it is often referred to as a gravitometer.

The most common types of accelerometers are piezoelectric, piezoresistive, and capacitive [3]. However, many of these devices are affected by electromagnetic fields and can not be used to measure constant or steady-state acceleration because of the inherent problems associated with their operating principles. These limitations motivated researchers to develop a number of different fiber-optic accelerometers [4-6]. In general, these optical units weigh less than their electrical counterparts and have relatively high signal-to-noise ratios. The optical fibers have the advantage that they are inert and immune to electromagnetic fields. Many of the intensity modulated optical devices are robust and relatively simple.

Rines, [7] for example, designed a one-dimensional accelerometer based on the intensity modulation produced by the lateral displacement of a cantilevered fiber relative to the entrance end of a stationary fiber. A small weight, attached to the cantilevered fiber, set the resonance of the

---

[1]The unit G is a nondimensional quantity which provides a measure of acceleration when the quantity is multiplied by the local gravitational acceleration, g = 9.81 m/s^2.

beam at the desired frequency, and the entire assembly was encased in a housing filled with damping fluid. The sensor was designed to be used as a hydrophone and had a high sensitivity to displacement for frequencies ranging between 10 Hz and 2 kHz. Soref et. al [8] reported on a simple compact, fiber-optic sensor that used a mirror placed on the end of a mass-loaded cantilever beam. Deflections of the beam due to acceleration were read out using a combination of multimode fibers and a quarter-pitch GRIN rod lens. The calculated minimum detectable acceleration was reported to be 2.1μG but fiber-deformation noise was found to limit the DC performance of the device. Dinev [9] improved on these designs and developed a simple and reliable two-dimensional fiber-optic accelerometer capable of measuring constant and variable accelerations simultaneously in two perpendicular directions. He employed a mass-loaded cantilevered fiber, suspended in a stainless steel tube filled with silicon oil. The movement of the fiber tip was magnified using a lens system so that it could be tracked using a dual axes linear position photosensor. This design looked very promising for the proposed application but the resolution was only 0.03 G's and the materials used for construction and sensing were not suitable for operation in a high magnetic field.

The problems associated with the Dinev accelerometer were overcome by suspending a magnetically nullified test mass on a horizontal length of single-mode optical fiber that is pre-formed and tapered. As illustrated in Fig. 1, the fiber is encapsulated within a circular glass tube. The tip of the fiber is imaged using a ball lens onto the image plane. Changes in the local gravitational field produce a deflection of the spot in the image plane; and, the deflection is measured and related to the acceleration.

As described below, this simple diffraction-limited image positioning device can be designed to have interferometric sensitivity. In view of its geometry and operating principle, the transducer is referred to as a *Transversely Suspended Accelerometer (TSA).*

DESIGN CONSTRAINTS

The researchers working on GS reported that the conditions of dynamic equilibrium resulted in an unvarying constant (DC) decrease in the gravitational field on the order of a percent, or, 10 milli-G's (mG); therefore, the TSA was designed to measure gravitational changes up to 20 mG. The limit of sensitivity and precision for measurement had to be at least several hundred times smaller than the latter, or, on the order of tens of μG's. It was also of interest to keep the physical size of the sensor as small as possible so that the highest spatial resolution could be obtained.

PARAMETRIC ANALYSIS

The mechanical response of the TSA was determined by solving a point-load beam deflection problem relative to the coordinate system illustrated in Fig. 2. The optical fiber was assumed to be a uniform cantilever beam of mass, m_f, and length, L. When the fiber is loaded at its free end with a mass, m, the elastic curve is [10]

$$y = \frac{mg}{6EI}(x^3 - 3Lx^2) - \frac{m_f g}{24EI}(x^4 - 4Lx^3 + 6L^2x^2) \quad (1)$$

where E is the elastic modulus of the fiber, and I is its area moment of inertia measured around a centroidal axis parallel to z. The natural frequency for this configuration is, [11]

$$\omega = \sqrt{\frac{3EI}{L^3(m + 0.235m_f)}} \quad . \quad (2)$$

The magnitude of the initial deflection, y_o, can be determined from Eq. (1) by setting x = L. Assuming that the mass of the fiber is small as compared to that of the end mass, and dropping the minus sign,

$$y_0 = \frac{m\ g\ L^3}{3E\ I} \quad (3)$$

where, for an optical fiber of diameter d, $I = \pi d^4/64$.

Changes in the deflection are found from,

$$\delta y = \delta g\ \frac{m\ L^3}{3E\ I} \quad . \quad (4)$$

Equation (4) can be used to establish the product mL^3 by choosing a range for δg and using the effective lens aperture for δy. The mass and fiber length can then be selected and the necessary initial deflection required for pre-stressing calculated. The resolution may be determined from the optical properties.

The sensitivity of the device was estimated by analyzing the mechanical system. To this end, an effective spring constant, k_{eff}, can be defined as,

$$F = k_{eff}\ y \quad (5)$$

where F is the applied force and y is the displacement measured from the initial position. For operation in 1 G, the equation,

$$m\ g = k_{eff}\ y_0 \quad (6)$$

gives the initial displacement, y_o, of the suspended mass, m. Assuming that a δg produces a corresponding δy, the sensitivity is given by,

$$\frac{\delta g}{g} = \frac{\delta y}{y_0} \quad . \quad (7)$$

The responsivity of the TSA,

$$R = \frac{\delta G}{\delta y'} = \frac{\delta g}{g\,\delta y'} \quad (8)$$

can be used to convert displacements of δy' in the image plane to μG's. This quantity is determined in terms of the effective spring constant and the effective mass, and these parameters can be measured experimentally to calibrate the device.

For a magnification M, δy' = Mδy, and

$$R = \frac{1}{g\,M}\,\frac{k_{eff}}{m_{eff}} \ . \quad (9)$$

PRELIMINARY DESIGN

Some empirical measurements were made to determine the elastic modulus of the fiber, optical magnification, and deflection range prior to the final design. The magnification was measured, for example, by translating the lens in a transverse direction using a micropositioner and measuring the deflection at the viewing plane. It was determined that the fiber displacement is limited to 0.36 mm before comatic aberration impairs image visibility. Within this range, the optical and mechanical systems were highly linear. By dividing the rated spot resolution by the viewing plane range, it was determined that the image position resolution was 0.105% full scale deflection: a design relation used to balance the overall range with the sensitivity limit.

In order to achieve the maximum sensitivity possible, the end of the 4 μm diameter, single mode fiber selected for the design was tapered down to provide a point-source image. When a HeNe laser (having a wavelength, λ = 633 nm) was used as a light source, the image in the viewing plane became an airy ring pattern with a small center spot. The spot size (FWHM), ss, is determined by the diffraction limit,

$$ss = \frac{1.22\lambda\, f}{a} \quad (10)$$

where f is the focal distance of the transfer lens and a is the diameter of the fiber tip.

Tapering the fiber end was found experimentally to provide a central image 6.05 times smaller than an untapered end. The rated resolution was chosen as 0.2 times this spot size; albeit, low-noise spot intensity measurement and analysis potentially allow an order of magnitude greater precision.

The overall size of the device was reduced by pre-forming the fiber. This was done by heating and shaping the fiber segment according to the opposite of the deflection curve determined by beam bending:

$$y = c\,(3Lx^2 - x^3) \quad (11)$$

where c = mg/6EI. Thus, when the mass was placed onto the fiber, the fiber moved to a straight line geometry. This allowed the sensitive portion of the accelerometer to be encapsulated in a very small straight tube.

DESIGN SPECIFICATIONS

The sensor for the advanced prototype was fabricated in a 16-step procedure involving fiber shaping, alignment/assembly procedures, and magnetic nulling. For the purposes of estimating the curve in Eq. (11), the single-mode optical fiber was assumed to have an elastic modulus of 68 GPa; the core and cladding diameters were specified by the manufacturer as 4 μm and 125 μm, respectively. A small lucite test mass having a length, width, and height of 4.9 mm, 3.6 mm, and 2.0 mm, respectively, was mounted on the fiber at a distance of 3.66 cm from the fixed support. The distance from the center of the mass to the fiber tip was 1.10 cm.

The lens was 2 mm in diameter with an effective aperture of 0.36 mm and a back focal length of 1.1 mm. When the device was tested, the magnification was established at 876 with the detector placed at a distance of 1 m from the lens; the spot size at this location was measured at 0.8 mm.

CALIBRATION

The prototype was calibrated by performing two measurements before encapsulation: a static deflection test to determine the effective spring constant, and a dynamic test to determine the effective mass. These quantities were put into Eq. (9) to determine the responsivity.

The effective spring constant was computed from the relation,

$$k_{eff} = \frac{g\,\delta m}{\delta y'}\,m \quad (12)$$

by placing a 0.1 mm sphere having a mass of 0.1 mg onto the test mass and measuring the deflection at the viewing plane. This process rendered a value of k_{eff} = 0.05 N/m.

Since there is very little damping of the intrinsic sensor, the resonant frequency, f, is given by,

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}} \ . \quad (13)$$

The period of oscillation was measured at 0.1912 s which, in conjunction with the effective spring constant, established an effective mass equal to 46.3 mg. By substituting this value into Eq. (9), the responsivity is 164 μG/mm. Since it is possible to measure 0.2 of the spot size (0.16 mm), the sensitivity of the TSA is 25 μG. The resonant frequency of 5.23 Hz (ω = 33 rad/s), measured during calibration, is obtained from Eq. (2) when the effective mass is substituted for the term in parenthesis.

MAGNETIC FIELD CONSIDERATIONS

First device tests revealed that the lucite mass responded by mG's to a small permanent magnet. This observation was considered important, since counter-arguments to the gravity reduction reported in the literature involved parameters such as air pressure, electric fields, temperature, and magnetic effects. The latter may deserve the most attention, since the experimental arrangements used to demonstrate GS typically require strong magnetic fields up to several Tesla.

To quantify the magnetic effects in the TSA, data were taken for the magnetic response of the test mass while suspended in the accelerometer arrangement. A small solenoid was calibrated and used to purposely apply a field with a high gradient. The graph included as Fig. 3 shows the deflection of the image at the viewing plane as a function of the DC voltage applied to the electromagnet. The two plots correspond to the untreated test mass, and the mass after uniform treatment with $FeCl_2$. Iron chloride and glass were the only materials tried, since optimization of these parameters was beyond the scope of the project. The results, although not linear, do show a dramatic reduction in the magnetic response.

CONCLUSIONS

The transversely suspended accelerometer is a simple diffraction-limited image positioning device designed to measure acceleration at low frequency in the vicinity of a strong magnetic field with interferometric sensitivity. In contrast to an interferometer, however, optical measurements are made independent of light intensity and polarization. The device can be made quite small and offers two-axis operation.

ACKNOWLEDGMENTS

Work was performed under NASA Contract No. NAS8-97095, Task H-28436D. The authors would like to thank their project managers, Mr. Ron Koczor (NASA/MSFC) and Mr. Whitt Brantley (NASA/MSFC), for providing the opportunity to conduct the research; project scientist Dr. David Noever (NASA/MSFC) for assisting with the technical development of the TSA; and, Dr. John Dimmock (UAH/Director, CAO) and Dr. Charles Lundquist (UAH/Director, CMDS) for reviewing and commenting on the work.

REFERENCES

[1] Podkletnov, E.E., Nieminen, R., "A possibility of gravitational force shielding by bulk $YBa_2Cu_3O_{7-x}$ superconductor," Physica C, 203: 441 (1992).
[2] Torr, D.G., Li, N., "Gravitoelectric-electric coupling via superconductivity," Phys. Lett. 6: 371 (1993).
[3] Karolys, A., Pender, G., "Present and future of acceleration and pressure measurement systems," *Proc.* 40th Annual Earthmoving Industry Conference, Peoria, Illinois, April 11-13, (1989).
[4] Layton, M.R., Danver, B.A., Lastofa, J.D., Bevan, D.P., "A practical fiber optic accelerometer," SPIE *Proc.* of Fiber Optic and Laser Sensors V, 838: 279-284 (1987).
[5] Brown, D.A., Garrett, S., "An interferometric fiber optic accelerometer," SPIE *Proc.* of Fiber Optic and Laser Sensors VIII, **1367**: 282-288 (1990).
[6] Su, W., Gilbert, J.A., Morrissey, M.D., Song, Y., "A general purpose photoelastic fiber-optic accelerometer," Optical Engineering, **36**(1): 22-28 (1997).
[7] Rines, G.A., "Fiber-optic accelerometer with hydrophone applications," Applied Optics, **20**(19): 3453-3459 (1981).
[8] Soref, R.A., McMahon, D.H., "Tilting-mirror fiber-optic accelerometer," Applied Optics, **23**(3): 486-491 (1984).
[9] Dinev, P.D., "Two dimensional fiber-optical accelerometer," Rev. Sci. Instrum., **67**(1): 288-290 (1996).
[10] Beer, F.P., Johnston, E.R., *Mechanics of Materials*, 2nd ed., McGraw Hill, New York (1992).
[11] Tse, F.S., Morse, I.E., Hinkle, R.T., *Mechanical Vibrations*, 2nd ed., Allyn and Bacon, Boston (1978).

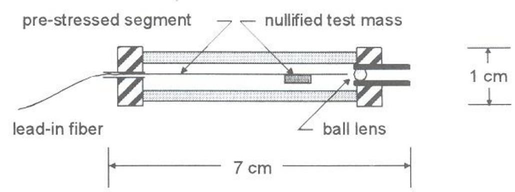

Fig 1. The Transversely Suspended Accelerometer.

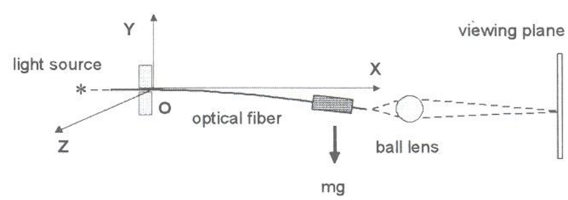

Fig. 2. Schematic of the measurement system.

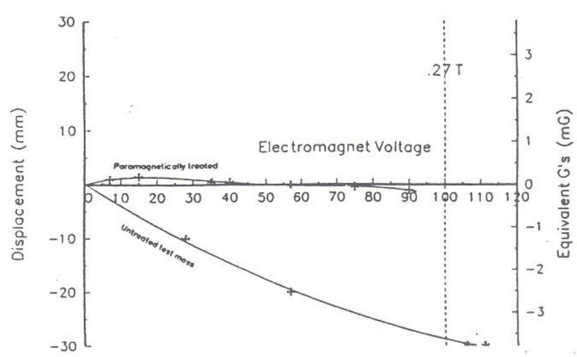

Fig. 3. Magnetic response of the TSA.