A Portable MEMS Gravimeter for the Detection of the Earth Tides

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***Abstract*— Gravimeters are used for measuring the local gravitational acceleration. The use of current commercially available gravimeters, however, has been limited by their high cost and large size. In this study, a microelectromechanical system (MEMS) based relative gravimeter with an acceleration sensitivity of 8 µGal/ √ (Hz) is demonstrated. The MEMS gravimeter, along with the custom interface electronics, is embedded on a battery powered portable platform. The portable platform enables continuous recording of the sensor response, while simultaneously measuring critical temperature and tilt parameters. To demonstrate the long-term stability of the system, the reported MEMS gravimeter platform was used to detect the Earth tides. In this paper, the first results from these measurements have been discussed.**

Keywords—MEMS, Gravimeter, Gravimetry, Accelerometers

I. Introduction

The ability to detect tiny variations in gravitational acceleration (*g*) using gravimeters allows measuring not just the Earth's gravitational pull, but the influence of smaller objects as well. Gravimeters are particularly useful for measuring the density variations of subterranean anomalies and, therefore, for detecting things difficult or impossible to see by other means. This capability can result in high impact, real-world applications of gravimeters in many exploitation areas. For example, gravimeters have been used in the oil and gas exploration industry [1, 2], in the defence industry to detect underground voids and tunnels [3, 4], in archaeology for detecting ancient ruins and structures [5], in the geophysical mapping of sub-surface voids and sinkholes [6], and in volcanology to monitor intrusion of magma during volcanic unrest events [7, 8].

Despite the demonstrable potential of gravimeters in subterranean imaging, high instrumentation cost, associated complexity, and large size have limited their widespread adoption and use. For example, a commercially available, field portable gravimeter with an exquisite sensitivity of 1 µGal/ √ (Hz) (where 1 µGal = 1 ng) could cost > £80k and can weigh ≥ 10 kg [9]. Further, such gravimeters have generally only been used for point measurements, and it is a financial risk to leave them unsupervised in remote locations.

Recently, researchers have developed MEMS scale accelerometers with sensitivities which are at comparable with the commercial gravimeters [10, 11]. These MEMS accelerometers, however, have not yet demonstrated long-term stability required for gravimetry. More recently, a MEMS-based gravimeter with excellent long-term stability, which promises at least an order of magnitude reduction in cost, size, and weight, has been developed by the authors [12].

While the authors have previously demonstrated the long-term stability of the MEMS gravimeter by measuring the Earth tides in a fixed laboratory-based set-up, similar measurements with a more practical, battery powered, field ready platform have not been reported yet. In this paper, the authors present the first results on the measurement of the Earth tides using a field portable MEMS gravimeter. The MEMS gravimeter, along with all the drive and readout electronics, is integrated on a small platform with automated temperature control and manually adjustable tilt. The reported MEMS gravimeter has an acceleration sensitivity of about 8 µGal/ √ (Hz) at 1 Hz, a factor of 4-5 better than the earlier reported version [12]. In the following sections, several aspects of the portable MEMS gravimeter platform will be briefly reviewed followed by a discussion on the latest Earth tide measurement results.

II. Sensor Description and Assembly of The MEMS Gravimeter Platform

The MEMS gravimeter (Fig. 1) being developed is a spring-mass system with a proof-mass of *m* and a spring constant of *k*. For a downward force of gravity, *F* (=*mg*), the displacement of the proof-mass *z* is proportional to *F*. The acceleration sensitivity of the gravimeter is calculated using the following expression (Eq. 1):

$$\Delta g = (k/m)\Delta z = \omega_0^2 \Delta z \qquad (1)$$

where, Δg is the minimum resolvable change in *g*, Δz is the minimum measurable change in the proof-mass displacement, *k/m* is the square of the angular resonant frequency, ω_0, of the spring-mass system. Hence, to improve the acceleration sensitivity when the gravimeter is limited by displacement noise, a lower resonant frequency is required. In the demonstrated device, an anti-spring flexure design is used to achieve a resonant frequency of 2.5 Hz. A detailed discussion on the flexure and device design can be found in reference [12].

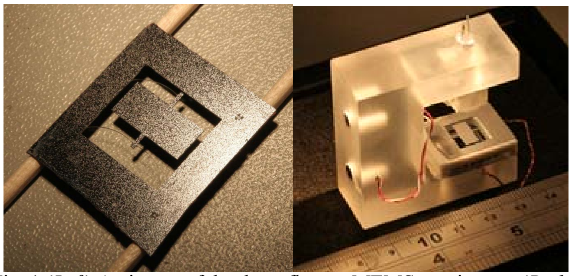

Fig. 1 (*Left*) An image of the three-flexure MEMS gravimeter. (*Right*) Image of the Silica C mount with LED on the top (not visible), and MEMS at the bottom.

A 220 µm thick single crystal silicon wafer is used for the device fabrication. After coating the wafer with a positive photoresist, a 'halo' mask design is used in conjunction with the Bosch process to etch and release the MEMS device [13]. This allows for a high aspect ratio etch which is necessary for the 6 µm wide, 220 µm deep flexures. A detailed discussion on the fabrication process has been reported in reference [12].

The displacement of the MEMS proof-mass is measured using an optical shadow sensor combined with a lock-in amplifier [12, 14, 15]. The proof-mass sits between an LED and a split photodiode. All the 3 components (LED, MEMS, and photodiode) are mounted on a small fused silica-C structure and placed inside a small vacuum chamber which itself is fixed on a small metal base plate. Any motion of the proof-mass affects the intensity of the light falling on the photodiode, thereby, producing a change in the photodiode output. *1/f* noise is effectively removed by modulating the LED signal and demodulating it at a later stage [15]. The optical shadow sensor in this platform has been demonstrated to have a displacement sensitivity of 10 nm/ √ (Hz) down to 3 mHz and a root-mean-square sensitivity of 1 nm over a period of 1 day [15].

As the device is sensitive to the alignment of the proof-mass with respect to the direction of gravity, any change in the tilt angle is expected to affect the sensor response. In the reported configuration, the device was measured to have a tilt sensitivity of 25 µGal/µRad in the out of plane direction of the chip and a tilt sensitivity of 0.3 µGal/µRad in the in-plane direction. To monitor and record tilt during experiments, a commercially available electrolytic tilt sensor was set up in a full Wheatstone bridge and attached to the platform. Three Vernier screws were also fitted to the base plate for adjusting tilt before the measurements were taken.

In the previously reported version of the MEMS gravimeter [12], the earth-tide measurements were carried out using a lab-based setup which required the use of commercial signal

Fig. 2 An image of the custom four-layer electronics board.

generation and read-out equipment. In the current version, a custom electronics board has been developed which integrates LED modulation drive, temperature sensors, heater outputs, current to voltage converters as well as other conditioning electronics on a small PCB (Fig. 2). Further, the current system can be powered using a battery. The temperature sensors and heaters, which are embedded in the platform, are controlled using a servo mechanism. This allows for a 1-2 mK temperature control of the device, thereby significantly reducing any temperature related spurious effects on the sensor response. Such significant improvements in the set-up have helped in making the platform small and low-cost. Several measurements using the integrated platform have been reported recently which demonstrate the field portability of the platform [16, 17].

III. Earth Tide Measurements Results

The Earth tides provide an excellent natural signal to test the sensitivity and long-term stability of gravimeters. The Earth tides are caused by the elastic deformation of the Earth's crust due to the gravitational pull of sun and the moon. The Earth tides can be diurnal or semi-diurnal depending on the relative positions of the moon and sun and have peak amplitudes of up

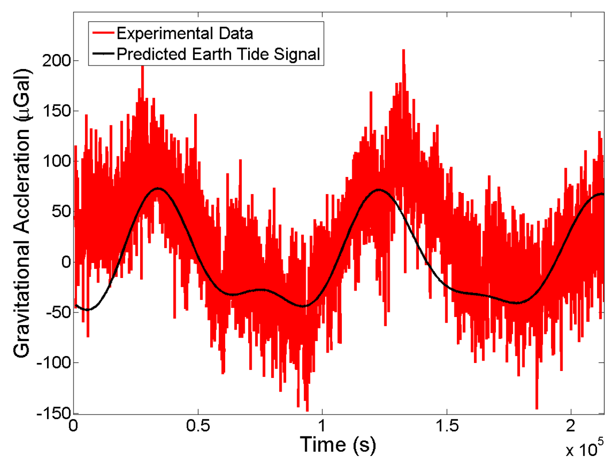

Fig. 3 Graph of the Earth tide time-series taken using the portable system. The expected tide signal obtained from the software TSOFT [19] is overlaid on the experimental data.

to 400 µGal [18]. Both the amplitude as well as the frequency

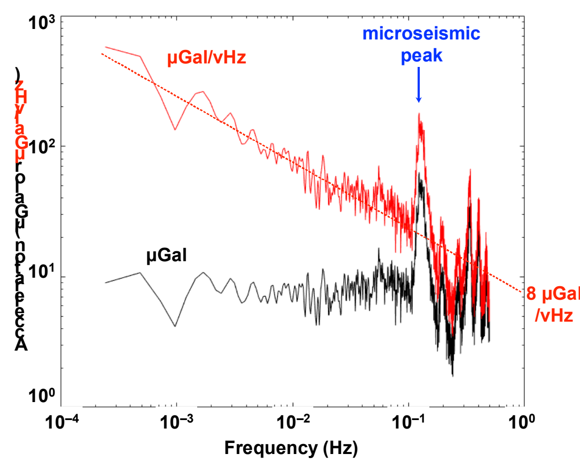

Fig. 4 Graph of the amplitude spectral density of the Earth Tide time series data. The plots show a microseismic peak at 160 mHz.

of the Earth tides are predictable, and their effect on local *g* can be precisely calculated.

In March 2018, the portable MEMS device was used to measure the Earth tides. A segment of the processed sensor time-series data is presented in the Fig. 3. The data presented was taken continuously over a period of more than two days (about 55 hours). The raw sensor data (not shown) was regressed against the recorded temperature sensors and tilt sensors data to remove the effect of temperature and tilt. Any linear drift was also removed from the raw data. In the figure, the experimental data is overlaid on the expected tide data. The expected Earth tide data is obtained from the TSOFT software [19]. A clear correlation between the experimental and the expected signal is visible from the plots. In the Fig. 4, the acceleration sensitivity (both amplitude spectral density and root-mean-square) of the MEMS device is presented. The sensor has an acceleration sensitivity of around 8 μGal/ √ (Hz) at 1 Hz. This is a factor 4-5 better than the previously reported measurements carried out using the bulky laboratory-based set-up [12]. The microseismic peaks are also clearly visible in the data.

IV. Conclusion

In this paper, a portable MEMS gravimeter platform has been used to detect the Earth tides. The device has an acceleration sensitivity of 8 μGal/ √ (Hz) at 1 Hz. The successful detection of the Earth tides demonstrates the excellent long-term stability of the reported portable platform. Further, the use of standard microfabrication technology to develop the MEMS device and the development of custom interface electronics is expected to reduce the overall cost of the portable platform. The above factors combined with the small form-factor of the platform will enable creating sensor networks, allowing multi-pixel 'images' of subterranean areas of interest as opposed to single point measurements carried out using expensive and bulky commercial gravimeters.

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