MEMS Gradiometers for Attitude Determination on CubeSats

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ABSTRACT

This paper presents the design, fabrication and testing of a new high sensitivity gravity sensor for attitude determination in CubeSats. The project is a collaboration between the Institute for Gravitational Research at the University of Glasgow and ÅAC-Clyde. The gravitational gradiometer takes advantages of the technology of microelectromechanical systems (MEMS) and determines the attitude of the satellite by a differential gravity measurement, the principle at the base of gravitational gradiometry. The capacitive readout allows to measure the rotation of the MEMS gradiometer and consequently evaluate the angle changes of the CubeSat. The developed geometry consists of two symmetrical masses connected to a fixed support by four thin flexure hinges. The all-Silicon sensor resonates at a frequency of 6 Hz, and has a total mass of less than 2 g. It is expected that the sensor geometry and the readout demonstrated would be suitable to achieve the performances required from CubeSat systems and detect a rotation of the small satellite of 1 degree, in order to offer performance comparable to other state-of-the-art sensors currently available on the market.

INTRODUCTION

Small satellites have become popular for space missions due to the balance achieved between high performance and low cost per unit. Small satellites, and specifically CubeSats, often share similar avionics across a wide range of form factors, thus introducing a diminishing return for payload volume at the lower end of the scale, for example a 6U (up to 4U payload) versus a 3U (up to 1.5U payload). This contrasts with the more attractive launch cost that smaller form factors enjoy, resulting in a more expensive $/U cost for the payload.

One of the largest avionic subsystems, in terms of volume, is the attitude determination and control system (ADCS), especially the sensors. The determination of the attitude of the satellite requires a wide range of sensors depending on the specific mission, which along with the volume constraints they introduce, also constrain the attitude of the spacecraft – for example, a star camera must be pointed at specific areas to function.

It is not technically feasible to simply remove these sensors, and thus finding an alternative sensor solution that is smaller and removes attitude restrictions, provides significant advantages. The characteristics of MEMS technology well suit this standard, allowing a reduction in mass, power consumption and cost of the sensors.

The development of a highly accurate CubeSat gradiometer will provide considerable benefit in future nanosatellite ADCS design.

PHYSICAL PRINCIPLE

Figure 1 shows a schematic diagram of a gradiometer. It consists of two masses connected by a fixed arm. This bar can be mounted on a central suspension (or pivot) so that it can rotate freely. If this apparatus is suspended in a gravitational field, a torque will be induced that depends on the angle of the arm relative to the gravitational field vector. This relationship can be explained by the Equation (1):

$$m(g_1 \cos\Psi - g_2 \cos\Psi)L = k\Phi \qquad (1)$$

where $m_1 = m_2 = m$ is the proof mass; g_1, g_2 are the gravitational accelerations acting on the proof masses; Ψ is the angle between the local vertical and the MEMS gradiometer; L is the length of the arm of each mass; k is the torsional stiffness of the suspension; and Φ is the rotation angle of the CubeSat.
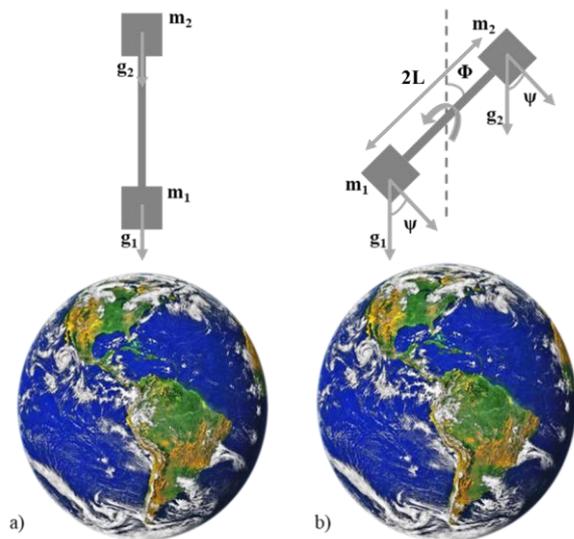
Figure 1: Schematic of the rotation of the MEMS gravity gradiometer in relation with the position of the Earth: a) m_1 and m_2 perpendicular to the Earth surface, b) rotation of the device of 45° respect to the original position.

The torque in this system is equal to zero when the arm is aligned either perpendicular or parallel to the gravitational field vector (the parallel case is displayed in Figure 1a). By contrast, the torque is maximised when the arm is oriented at an angle of 45 degrees relative to the field vector (as displayed in Figure 1b). The torque varies sinusoidally for angles in between these two extreme cases [1].

DESIGN OF THE SENSOR AND FABRICATION

The sensor design was undertaken considering the design constraints detailed in the above section. To achieve the required sensitivity, the geometry developed needs to be soft in the direction of the first mode of resonance and stiff in the direction of all other modes of resonance. This means that a small value of frequency (of the order a few hertz) is required for the first mode of resonance and a value as bigger as possible is required for the second mode of resonance in order to guarantee the desired stiffness. The high ratio between the first and second modes is required to ensure a minimal motion of the sensor outside of its sensitive axis.

To test the efficiency of the suspension structure considered, and to estimate the resonant frequency of the sensor, a finite element model has been developed using ANSYS. Several geometries have been analysed in order to match the sensitivity requirements, robustness and the fabrication constraints.

The proposed geometry consists of a fixed support in the middle, four long hinges that connect the two proof masses to the fixed support, and two side arms to increase the robustness. After defining the geometry, the study focused on understanding the variation of the resonance frequency and consequently the sensitivity, in relation to the length and the width of the hinges, the angle of separation between the hinges, and the overall dimensions of the sensor.
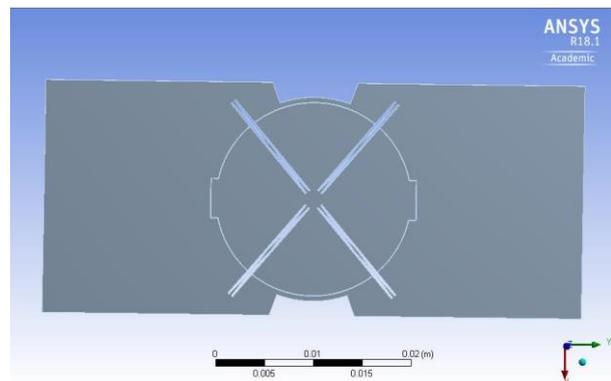

Figure 2: Capture of the MEMS gradiometer from ANSYS model

The geometry shown in Figure 2 is novel in terms of the design of the hinges. These are shown in Figure 3 to have a width of 250 μm which decreases to 20 μm at two points. The etch process is one the most critical during the fabrication and the new geometry presents six points where a careful etch process is required.
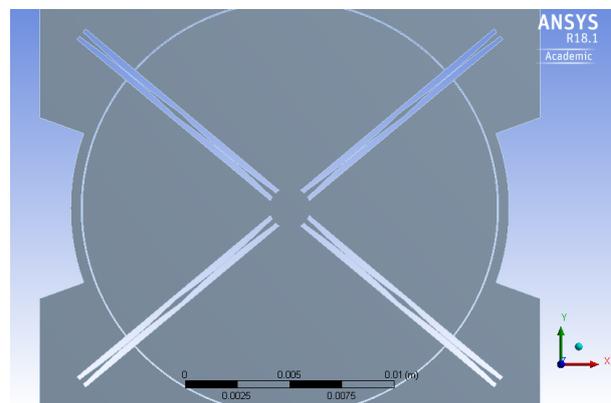

Figure 3: Front view of the four hinges of the gradiometer geometry

The chosen geometry with an overall length of 5.6 cm and width 2.7 cm turns out to be extremely soft in the direction that allows the reading of the rotational torque presenting the first mode of resonance at 6 Hz. The resonant frequency of the second mode is almost five times greater than the first mode (33 Hz), which guarantees the stiffness required for the second mode to

ensure the correct reading of the system output. A few geometries have been analysed in order to identify the chosen design of the flexures. This design, as well as providing the required stiffness in the direction of the second mode of resonance and above, ensures low stress improving the overall robustness of the sensor.

By using the facilities of the James Watt Nanofabrication Centre at the University of Glasgow, the fabrication of the sensors has been carried out. A layer of silicon dioxide is deposited on the back side of a double side polished 4-inch silicon wafer. After a dehydration process, a layer of primer and then a layer of the resist are spun onto the top face of the wafer. The wafer surface is exposed to UV light to pattern the sensor geometry. The sample is etched using the Bosch process [2]. The suspended structure is slid onto a silicon carrier wafer after a methanol bath, and then a plasma ashing process is used to remove the residues of resist from the top face of the wafer. The release of the MEMS gradiometer is completed by etching the silicon dioxide on the bottom face of the wafer.

Figure 4: Prototype of the silicon MEMS gravity gradiometer

Figure 4 shows the prototype of the MEMS gradiometer. The overall length of the sensor is 5.6 cm

MECHANICAL TEST

The first test performed on the MEMS gradiometer has been the measurement of the first mode of resonance. The sample was mounted between two Silica wafers, and small pieces of 250 um thick Silicon wafer were used as support to create a gap between the glass wafers and the sensor.

The sensor was excited by rotating the package, and then filmed with a high-speed camera (210 frames per second). The footage was used to calculate that the resonant frequency of the sensor was 6.6 Hz. To make sure that the frequency was measured to the greatest accuracy possible, ten oscillations of the MEMS sensor were observed. At 210 frames per second, ten oscillations would take 317 frames.

To verify the accuracy of the first measurement a shadow sensor read-out has also been implemented [3]. The rotation of the device is measured. The packaged sensor was fixed onto a stage by using crystal bond (Figure 5a). The sensor was excited by blowing compressed air between the two glass wafers. The edge of the sensor was illuminated by using a laser, and the light was collected by a split photodiode connected to signal conditioning electronics (trans-impedance amplifiers, filters, etc.). The change in intensity incident on the photodiode resulting from the rotation of the MEMS gradiometer shadow was then used as a measure of the rotation.

The resonant frequency measured by using the shadow sensor is 6.25 Hz (Figure 5b), confirming ANSYS analysis.
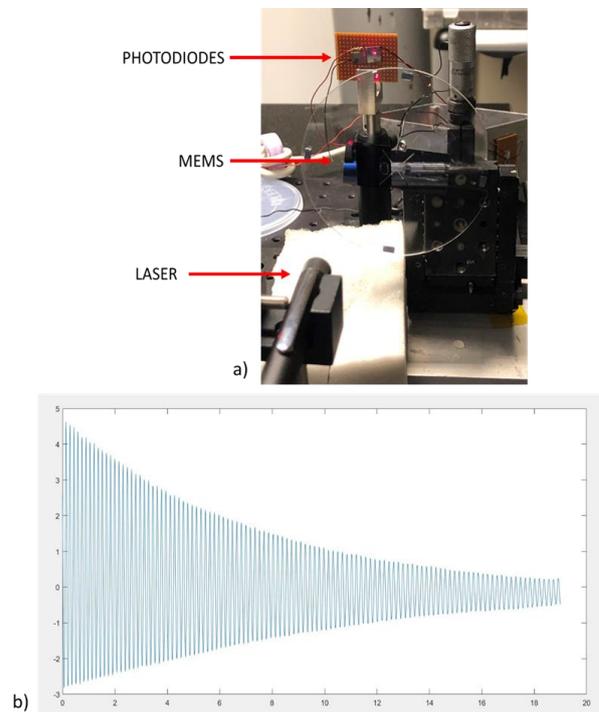

Figure 5: a) Shadow sensor setup for the measurement of the first mode of resonance; b) Plot of the ring-down measured shadowing the oscillating MEMS gradiometer.

READOUT OF THE MEMS GRADIOMETER

The displacement of the system will be monitored with a capacitive readout mechanism. A series of metal electrodes will be patterned on the surface of the moving parts of the MEMS device, forming a 'comb' structure. A drive signal will be passed through these electrodes. A corresponding comb structure will be placed on a second layer, that will be affixed above the moving electrodes; this structure will act as a pickup.

By monitoring the signal induced in the pickup, the torsional motion of the MEMS can be ascertained.

The signal processing of this system will be conducted using a field programmable gate array (FPGA) electronics board. This board will used to create the drive signals on the MEMS electrodes, and to monitor the signal from the pickup.
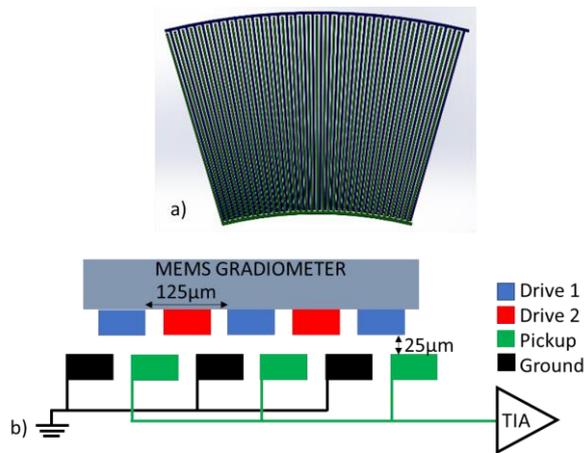

Figure 6: a) Radial spaced electrodes; b) Schematic of drive and pickup electrodes

An analysis of the variation of the overall capacitance when the inner pickup electrode rotates by 1°, starting from the position of perfect overlap with the inner drive electrode, has been developed using Comsol Multiphysics software. This allowed to estimate the gradient of capacitance, that is 1464.5 pF/rad. The sub-attofarad sensitivity of the readout circuit (0.5 aF/rt(Hz) @1Hz) achieved by Dr Abhinav Prasad and Andreas Noak, combined with the estimated gradient of capacitance, allows the detection of a rotation of the CubeSat of 1°.

Following the theoretical analysis, the electrodes have been patterned on PCB boards in order to verify the match with COMSOL simulations, verify they have a symmetrical response, study the effect of ground-comb on the capacitive gradient and of ground planes on the noise.

CONCLUSION AND FUTURE WORK

The design of a novel MEMS gravity gradiometer for attitude control in CubeSats with capacitive readout has been presented. The flexure hinge geometry shows a fundamental frequency of 6 Hz for an all-silicon sensor with a mass of 1.6 g. The readout system consists of two drive and two pickup electrodes, connected to a trans-impedance amplifier-based read-out scheme. Numerical simulations suggest the sensor design is promising to achieve detection of a 1° rotation of the

CubeSat. Notably, the sensor has the ability to operate in both sun-light and eclipse conditions and is therefore likely to remove the need for multiple sensors, therefore increasing the available volume within the CubeSat platform. The next step of the project will be to perform initial testing of the sensor. These tests will include vibration tests to verify the robustness of the sensor and measurement of the second mode of resonance using an optical lever. The radial spaced electrode will also be fabricated using standard micromachining techniques and then tested. Finally, further work will be required to integrate the electrodes with the sensor.

References

List and number all bibliographical references at the end of the paper. When referring to references in the text, type the corresponding reference number in superscript form as shown at the end of this sentence.**Error! Reference source not found.** Use the **References** style for formatting citations, as shown in the following examples:

1. K. Ghose, "MEMS Inertial Sensor to Measure the Gravity Gradient Torque in Orbit," PhD Thesis, 2012.

2. F. Laermer and A. Schilp, Method of anisotropic etching of silicon, US patent number: 5501893A, 1996.

3. Carbone, L. et al., "Sensors and actuators for the Advanced LIGO mirror suspensions," Class. Quantum Gravity 29, 115005, 2012.