Could MEMS-based accelerometers be used for gravity surveys?

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ABSTRACT

Recently published results show promising developments in using MEMS-based accelerometers to record static gravity at microgravity-scale resolution. The challenge of adapting MEMS accelerometers from the seismic realm to the task and their potential to be a good platform for development are presented, and several advances are suggested to improve their very low frequency and static performance. An implementation is envisioned that would add a dedicated gravity-measurement chip to a seismic sensor, and provide microgravity data with minimal added cost in the field.

INTRODUCTION

A sensor (or multi-sensor unit) capable of detecting both seismic events and micro-g changes in the static gravity field would be of great value to the geophysical and engineering communities (Alshakhs et al., 2008). In an oilfield monitoring setting, it would allow high-precision, constant and inexpensive monitoring of both microseismic events and density changes related to production of oil and gas. In an exploration setting, it would make high-resolution gravity surveys less expensive and easy to acquire, for basement studies and density constraint for inversion and imaging.

At present, MEMS-based accelerometers used for oil and gas seismic sensing are not well suited to microgravity measurement, as they are optimized for capturing seismic signals in the 5-500 Hz range. While it is well known that MEMS accelerometers have a DC response, and geophones do not, seismic MEMS accelerometers are not presently reported as capable of detecting μg-scale changes in the gravitational field.

Krishnamoorthy et al. (2008) recently showed that MEMS-based accelerometers have the ability to make microgravity measurements (Figure 1). The chips discussed in that paper are based on high-resolution optical gratings rather than capacitors, but they are open-loop, not built around a delta-sigma digital feedback. The feedback principle could be a means to bridge the gap in sensitivity between capacitors and optical gratings. The ideas used to reduce instrumental noise sources in the optical grating sensors may be also adapted to capacitive accelerometers to improve low frequency signal to noise and permit μg measurements.

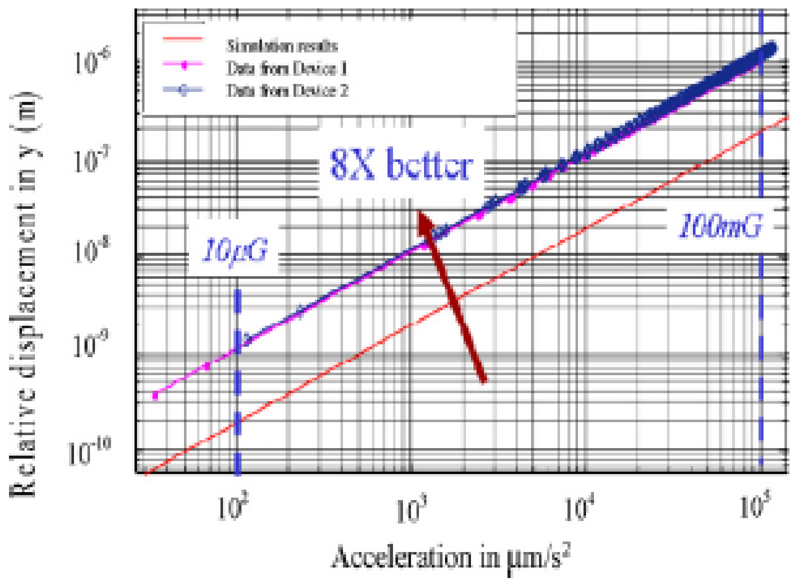

FIG 1. Static response of an open-loop, optical grating based MEMS accelerometer (Krishnamoorthy et al., 2008). 10 μm/s^2 is equivalent to about 1 μg. The measured noise floor is down to 0.1 Hz is equivalent to 17 ng/√Hz.

THE CHALLENGE

Measurement of sub-μg signals at very low frequency is a huge technical challenge, as suggested by the cost of modern gravimeters. There are two major categories of gravimeters. First, absolute instruments, often using a weight-drop that tracks the motion of a freefalling mass in an evacuated chamber, and secondly, relative gravimeters, often based on zero-length springs, which balance the spring force with gravitational force (Chapin, 1998). Both types are able to achieve resolution well below 0.1 μg, sometimes below 1 ng, and are able to detect the free air anomaly of several centimeters change in elevation.

It is not reasonable to suggest that a MEMS-based accelerometer will challenge the resolution and accuracy of industry-standard gravimeters. Nonetheless, a gravity survey with more than an order of magnitude lower resolution than modern gravimeters (~0.1 μg) could still be of significant use. At present, MEMS accelerometers are stated to have an ability to detect their tilt angle, but the tilt resolution of current ION VectorSeis and Sercel DSU systems is around 1°. That error is equivalent to 17.4 x10^3 μg, over five orders of magnitude larger than required for microgravity surveys. However, this may be a pessimistic assessment of the accelerometers' abilities. Determination of the tilt angle relies on comparison of the three orthogonal accelerometers to determine the total gravity vector (ION technical note). This is simple and practical in the field, but largely limited by the orthogonality of the sensor chips within the packaging (Figure 2), which at present are specified to approximately 0.25°. If the sensor chips are not precisely orthogonal, the estimated tilt will be in error, and the length of the total gravity vector will change with tilt angle, making it impossible to separate changes in the gravity field from changes in tilt.

The angle of a gravimeter must be known to ~50 arcseconds (0.014 degrees) for better than 0.1 μg resolution (Rymer, 1988). If this is achieved, it brings the possibility of measuring very precise tilt readings at the same time as gravity. If not, however, the inability to know or carefully set the orientation with this precision makes measuring micro-g signals impossible, even if the DC accuracy of a single element can provide the required noise specification. If this precision is not achievable when mounting the chips within the sensor case, 360° rotation of each sensor through two orthogonal axes may be required to characterize the internal orientations of the sensing elements, or a gimball mechanism to keep the gravity sensor vertical.

FIG 2. Cutaway of the three MEMS accelerometers mounted within a VectorSeis frame (Maxwell, 2001).

Under dynamic accelerations (>3 Hz for Vectorseis and >10 Hz for DSU), MEMS accelerometers already have noise floors in the range required for micro-g measurement. For example, the VectorSeis system is quoted at 607 ng for a bandwidth of 250 Hz, or 38.4 ng/√Hz. At very low frequency, however, noise contributions which have no significant impact to higher frequency measurements can become a large problem. In particular, 1/f noise in the sensor's reference signal and amplifiers can dominate the output (Krishnamoorthy et al., 2008).

Reductions in the overall noise floor of instruments generally involve increasing the sensitivity. The simplest way to do this in a spring-mass system is to soften the spring or make the mass larger so the relative motion of the mass will be more detectable. The problem is that if the proof mass motion is much larger and more detectable, the sensor is also more easily damaged by shocks. The MEMS chip developed by Krishnamoorthy et al. (2008) achieves its extremely low noise floor by combining the remarkably low resonance of 36 Hz with several noise reduction techniques within the instrument. The authors note that such a compliant suspension system compromises the robustness of the sensor. The low resonance also means this sensor is not an accelerometer for seismic signals, but it does retain its flat response for signals of frequencies less than 20% of resonance. Overall, maintaining shock-resistance while lowering the noise floor requires more accurate recording of the position of the proof mass, and the noise reduction techniques suggested by Krishnamoorthy et al. may be able to help accomplish this in capacitive MEMS chips.

A challenge particular to the digital MEMS accelerometer is that the proof mass must be kept near the center of the chip to stay within the linear range of the suspension. If the digital feedback is the only means used to accomplish this, as is the case with accelerometers used in the seismic industry, the sensor must effectively record the full gravity value, with accuracy down to 100 parts per billion (-140 dB). This is right on the edge of 24-bit dynamic range (144 dB). The simple answer is to partially compensate for the bulk of gravity some other way, but this will result in a limited range of tilt angles where the chip is operable, as was true for the Sercel DSU408 (but not the updated DSU428).

Finally, even if a sensor is accurate and has the desired resolution, the sensors must all be calibrated to each other at the start of a survey to account for drift during storage. If many sensors are distributed around a survey, as is the case with seismic exploration, rather than using the same instrument at all stations, as in most gravity surveys, instrument drift must be assumed to be negligible.

ADVANTAGES OF THE DIGITAL ACCELEROMETER

Perhaps the greatest advantage of an effort to use MEMS accelerometers for microgravimetry is simply their size and cost, relative commercially available gravimeters. A MEMS chip is small, robust and can operate on a reasonable power supply (<500 mWatt). This provides the option, if required, of creating a specialized low frequency accelerometer for gravity applications, and including it within the seismic sensor package. Until self-noise can be brought down throughout the frequency range (down to very near DC), this may be the most reasonable solution.

While averaging in airborne surveys and multiple readings at a station are common, commercial gravimeters are not based on an averaging architecture, so the measurement taken at any instant must have the accuracy required by the survey. Some gravimeters apply electronic feedback to steady vibrations in the measurement device, but no commercially available gravimeter uses digital feedback output to directly measure gravity. Seismic MEMS accelerometers, on the other hand, are built on a delta-sigma (ΔΣ) analog-to-digital conversion architecture. It is an excellent means of converging to an accurate representation of a low-frequency input signal by averaging many poor-resolution, inaccurate samples. Convergence to a constant value is extremely quick (Figure 1), and the noise floor of the technique is limited only by how many samples are averaged, known as the oversampling ratio (OSR). Since many hundreds or thousands of samples are averaged to give a single output value, the output sample result can be equivalent to a reference mass position much smaller than the sensor could detect at any given time. One µg is 1 millionth of the full signal, and Figure 3 shows that to achieve this noise floor about 2^{20} (1.05×10^6) samples must be averaged. Modern MEMS accelerometers' ΔΣ loops sample at least 128,000 times a second, so this represents at most ~8.2 seconds per output. This is an idealized estimate that does not take into account noise sources within the sensor that may need to be averaged.

The noise shaping of this technique is so powerful that running it long enough to average out any long-period 1/f and other noise sources may be all that is required to obtain an acceptable gravity measurement (assuming known perfectly vertical orientation). This would essentially constrain the frequency band of the output to small fractions of 1 Hz. Predicting how a multi-order ΔΣ process will shape its own 1/f noise is difficult, however, and physical experiments comparing a digital MEMS accelerometer, modified output a sample only every couple of minutes, with a commercial gravimeter would be the best way to investigate.

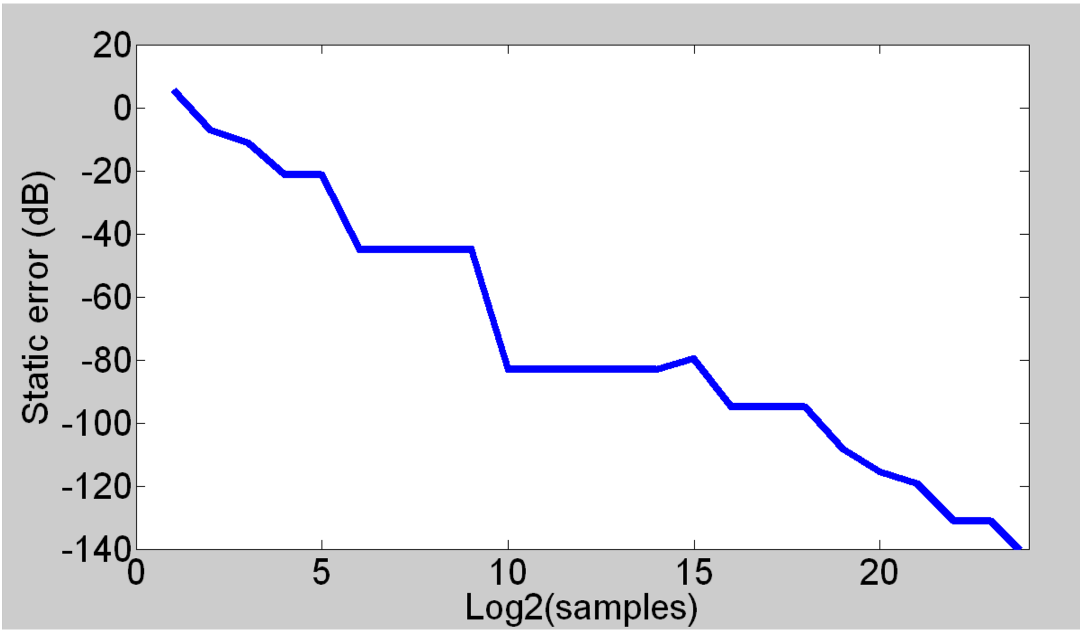

FIG 3. Static noise floor of a 5th order ΔΣ modulator vs. samples averaged.

Seismic-grade MEMS accelerometers have several other important advantages that make them suitable as a base to create a high-precision gravimeter:

- they are very precisely machined, and their tolerances are very close
- the 'springs' supporting the reference mass are very stiff, and the reference mass very small, which may help reduce drift over the length of a survey
- the electronic suspension keeps the physical spring within its linear range while measurements are being taken, again hopefully reducing drift
- the packaging of the chip is evacuated so that random vibration of air molecules does not add to the instrument noise (and also provides excellent barometric and temperature insensitivity)
- the voltage applied during feedback does not need to remain perfectly constant, as long as it can be assumed to be symmetrical throughout the number of ΔΣ loops that contribute to the output.

While these reasons outline the potential for creating a capacitive-feedback MEMS accelerometer for gravity surveying, advances may need to be made.

POTENTIAL ADDITIONAL IMPROVEMENTS

Low frequency noise in the voltage applied to the sensing capacitors (e.g. drift, small differences on power-up, 1/f noise) will have a harmful impact on the ability of the sensor to achieve high-precision low frequency measurement. In particular, the current through the circuit will have noise in it from various sources (e.g. Brownian, 1/f, amplifier, etc.). The very low noise MEMS-based accelerometers mentioned in the introduction (Krishnamoorthy et al., 2008) rely on interference of laser light through optical gratings to determine the position of the proof mass, and they encounter similar problems in the quality of the laser light. These problems are addressed through correlated double sampling, which involves holding the observed differences from ideal current in a dedicated hold capacitor first, then performing the sensing phase through the sense capacitors are removing the observed noise from the sensing phase output (Wongkomet and Boser, 1998). The symmetry of the ΔΣ loop (e.g. sensing with two capacitors on either side of the reference mass) likely reduces the sensitivity of the instrument to this noise, but a concerted effort to eliminate it would likely yield better results.

It may be necessary to opt for changes in engineering the chip, like a larger proof mass or using optical gratings instead of capacitors. This may make it difficult to maintain the robustness required for field sensors. Nonetheless, borrowing from them may be able to improve the low frequency handling of a capacitive sensor to the levels required.

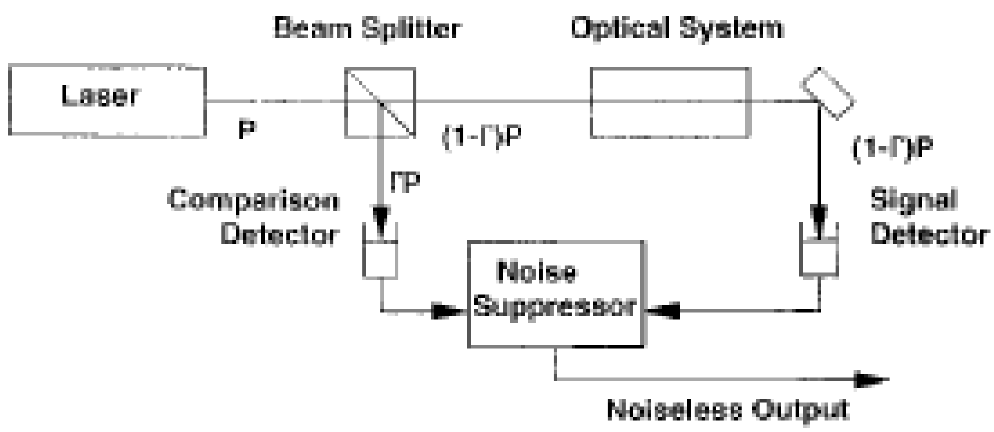

FIG 4. Block diagram of double correlated noise suppression, for a laser source (Krishnamoorthy, 2008).

SUGGESTED IMPLEMENTATION

While an accelerometer with a selectable mode capable of either seismic recording or microgravity and high precision tilt measurement would be the ideal outcome of an effort to improve the low frequency characteristics of MEMS accelerometers, this may prove unrealistic with present technology. A better solution may be to focus on the refinement of a separate gravity-sensing MEMS chip, to be housed within the same field unit as the seismic sensors.

This approach has some strong advantages: the gravity sensor, which may require a higher sensitivity than the seismic sensor and may thus be less resistant to shocks, can be vibrationally isolated (i.e. suspended) in a gimbaled or floating packaging that automatically orients to vertical. This makes the combined sensor robust enough for common field use, eliminates some of the noise coming through the earth, and eliminates the need for costly orthogonality measurement of the seismic sensors or careful orientation in the field. The gravity output need only be a single number recorded every few hours or days, and may be stored in a seismic header so a dedicated channel is not required.

In any of the implementations imagined here, the sensitivities must be compared just before the survey to eliminate drift from storage and transport. This would simply involve powering up all of the gravity sensors for enough time to perform a few measurements. All sensors would need to be fairly close together, both laterally and vertically. Their gains could then be recorded, and after this small delay the sensors could all be laid out as usual. Very little would be added to the cost of a survey besides the extra drain on batteries.

CONCLUSIONS

Microgravity from microchips is here; other researchers have shown MEMS-based accelerometers can be made sensitive enough to record microgravity surveys. Easier recording of microgravity data could be of great interest to geophysics, to monitor production and provide density inversions. Either seismic-sensing accelerometers may be adjusted to improve their noise at very low frequencies, or a dedicated gravity-sensing chip may be added to conventional seismic sensors. The challenge of recording extremely small gravity changes, especially those associated with production, is great, but the integrated ΔΣ-based recording of MEMS accelerometers, along with their high-precision manufacturing and drift insensitivity, make an intriguing platform to address the problem. The solution may as simple as unleashing the power of the ΔΣ loop on millions of samples rather than hundreds (as is the case with 1 or 2 ms seismic output), or as complicated as optical gratings and internal noise control.

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