A MEMS gyroscope for Reliable Long-Duration Measurement While Drilling at 300°C

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ABSTRACT

To increase the efficiency of drilling unconventional geothermal wells, new technology is needed that maximizes drilling effectiveness while minimizing cost. An important research topic is the measurement while drilling (MWD) system that navigates the drill string to the desired location underground. In conventional oil and gas drilling, MWD systems are typically designed to operate at temperatures <175°C, making them unsuitable for drilling enhanced geothermal systems where the downhole sensors and electronics may need to tolerate sustained temperatures of 300°C or more. In this hot environment, new sensing technology is needed that results in MWD tools that operate continuously at 300°C while being safe, accurate, and reliable. To fill this need, we are developing a high temperature, MEMS-based (micro-electromechanical system) gyroscope for continuous operation in a 300°C geothermal drilling environment. Unlike conventional MEMS gyroscopes that are limited to relatively low temperature operation (<125°C), the MEMS gyroscope we describe herein is capable of navigation grade performance and continuous operation at 300°C without the use of heat shields, or other passive/active cooling hardware. To achieve this, our team at GE Research designed a new MEMS gyroscope called a Multi-Ring Gyroscope (MRG) that is specifically optimized for high temperature operation in harsh environments, and under Department of Energy (DOE) award number DE-EE0008604, we are currently fabricating test devices and working to couple them to a custom Application Specific Integrated Circuit (ASIC) fabricated using silicon-on-insulator electronics. In this contribution, we provide an overview of our research program and give an update on our progress to date. This includes a discussion of gyroscope performance requirements, a survey of commercially available MEMS gyroscopes, an overview of the MRG design, and presentation of our latest MRG component validation results over the temperature range 25-500°C.
1. Introduction

Geothermal energy is a clean and efficient source of energy that has the potential to become an important component of the United States energy portfolio (MIT report, 2006). To achieve this clean energy future, the economic costs to access unconventional geothermal resources requires new technology innovation that increases the efficiency and effectiveness of drilling geothermal wells. One substantial challenge is the geothermal drilling environment is hotter than the typical oil and gas drilling environment, making it necessary to design new drilling technologies, methods, and tools specific to geothermal environments (DOE Technical Report, 2019).

In conventional oil and gas drilling, a sensor package positioned downhole determines the orientation of the drill string using accelerometers and either magnetometers or gyroscopes, in a navigation tool referred to as measurement while drilling (MWD) or sometimes gyro while drilling (GWD), respectively (herein we refer to both MWD and GWD as MWD, unless stated otherwise). To enable MWD in unconventional geothermal drilling, the sensors and signal processing electronics should reliably operate continuously at 300°C, which is significantly hotter than the temperature capability of existing MWD or GWD tools (typically specified for <175°C operation). Clearly, the cost of drilling a geothermal well will increase if the drilling operation is ineffective, or if the tool has significantly reduced lifetime or fails unexpectedly.

A program to develop a 300°C MEMS gyroscope for geothermal drilling has been awarded to GE Research, in collaboration with InertialWave, by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Geothermal Program Office (award number DE-EE0008604). At the conclusion of this 2-year program, GE Research and InertialWave will deliver a 300°C capable gyroscope containing a high-temperature optimized MEMS gyroscope and silicon-on-insulator (SOI) based control ASIC. GE Research will also leverage its reliability expertise in high temperature electronics to demonstrate functionality and lifetime beyond 1000 hours (Shaddock, 2010 and Zhang, 2012).

The high temperature optimized gyroscope is based on GE Research’s patented Multiple-Ring Gyroscope (MRG), which is well suited for downhole environments. The MRG design includes multiple concentric rings as the proof mass. The operating principle of the MRG is based on Coriolis force which transfers energy between two degenerated wine glass resonant modes. The raw analog signal from the MRG is processed by a frontend and feedback control ASIC based on silicon-on-insulator electronics processing technology. Unlike conventional silicon processing which is limited to relatively low temperatures (<120°C), SOI-based electronics can operate safely and reliably at 300°C.

This program consists of two phases, which are design feasibility & component validation, and system demonstration. We are currently in the first phase where we are testing the MRG at the component level using benchtop electronics (the control ASIC has been designed and is being fabricated). In this contribution, we first discuss a gyroscopes performance requirement for MWD and then survey existing commercial-off-the-shelf (COTS) devices. Afterwards, we discuss the MRG design for high temperature, and then present the component validation data for the MRG showing functionality over the temperature range 25-300°C and survivability of the MRG transducer up to 500°C.
2. Gyroscope Performance Requirement for MWD

To establish a basic gyroscope performance requirement for MWD, we used the error model governed by the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) to quantify the relationship between the gyroscope measurement uncertainty, the azimuth uncertainty, and the well path uncertainty (Williamson, 2000 and Torkildsen, 2008). The transfer functions that we use here do not model a specific gyroscope-tool but rather are intended to serve as a performance entitlement that can serve as a general, rule-of-thumb discussion guide.

2.2 Gyroscope impact on Azimuth Uncertainty

We analyzed the impact of the MEMS gyroscope uncertainty on the azimuth uncertainty. To determine the relationship between gyroscope measurement uncertainty and azimuth uncertainty, we propagated the gyroscope error through transfer functions that convert the gyroscope output into an azimuth measurement.

The primary gyroscope error source we consider here is the bias instability. Other important error sources, like vibration induced errors, random noise, and g-dependent errors, will become important if the bias instability results in a performance entitlement offering the possibility of 300°C MWD. Therefore, for brevity at this relatively early stage of development, we do not go into discussion of those error sources here, but we do note they can become important sources of performance degradation that we will consider as our technology matures. In the modeling results discussed here, we have fixed random noise, scale factor, misalignment, and g-dependent errors to values we feel are achievable and consistent with current MWD systems.

We used two models; the first is the ISCWSA error model and the second is a custom model that uses a GE proprietary carouseling algorithm. This carouseling algorithm was chosen to show the potential impact of algorithm design.

The ISCWSA model assumes that three gyroscopes are placed orthogonal to one another and used to measure earth rate directly. The proprietary algorithm assumes a single gyroscope is rotated in-plane and used to sense the modulation of earth rate as the gyroscope is rotated (i.e., the gyroscope output is maximized when pointing north, minimized when pointing south, and null when pointing east or west). A sinusoidal curve is fit to this modulated output and the phase offset is used to determine azimuth. The results from both algorithms are shown in Figure 1.

In Figure 1 we see that a bias instability of 0.1°/hr results in an azimuth uncertainty of approximately 0.5 degrees, and a bias instability of 1-10 °/hr results in an azimuth uncertainty of approximately 5 - 50 degrees, respectively. Typically, in MWD and other navigation applications, an azimuth uncertainty of <1° is needed, which suggests a bias instability of approximately 0.1°/hr should be targeted at the operating temperature.
Figure 1: Azimuth uncertainty as a function of the bias instability of the gyroscope. To achieve azimuth uncertainty of 0.1 - 1° a gyroscope must have a bias instability in the range of approximately 0.01 - 0.1°/hr, respectively.

2.3 Gyroscope impact on Wellpath Uncertainty

To quantify how the well path uncertainty can relate to the gyroscope uncertainty, we plotted the semi-major axis of the ellipse of uncertainty (EOU) for ISCWSA well #1 (Williamson, 2000), using both a standard MWD model (based on magnetometers) and a MEMS-gyroscope based model we labeled as GWD (Figure 2).

Figure 2 shows visually that the well path uncertainty for the MEMS-based GWD tool is comparable to MWD when the bias instability is approximately 0.1 °/hr, and becomes significantly larger with bias instabilities of 1 - 10 °/hr. To see this relationship more clearly, Figure 3 shows the EOU at 8000m plotted as a function of the bias instability.

Figure 2: The ellipse of uncertainty for ISCWSA well #1 for the MWD model (dotted) and Gyro model (solid) with bias instabilities of 10, 1, 0.1, and 0.01 °/hr.
To achieve similar performance as standard MWD the gyroscope in our model must have a bias instability of approximately 0.1 °/hr.

Figure 3 again shows that the MWD and MEMS-based GWD models are comparable in performance at a bias instability of approximately 0.1 deg/hr. Unfortunately, with bias instabilities of 1 deg/hr and 10 deg/hr, the EOU increases by approximately 1,000% and 10,000% respectively. Therefore, if a MEMS-based gyroscope greatly exceeds 0.1 deg/hr in the geothermal drilling environment we expect that significantly higher position uncertainties will need to be tolerated.

3. Survey of COTS devices

We surveyed the availability of navigation-grade MEMS gyroscopes from the vendors listed in Table 1. For comparison, we also included examples of a dynamically-tuned gyroscope (DTG), a hemispherical resonator gyroscope (HRG), and a fiber optic gyroscope (FOG).

The most precise MEMS gyroscopes we were able to obtain publicly-available data sheets for have bias instability and angle random walk values on the order of 0.1 °/hr and 0.01 °/rt(hr) respectively. This is comparable to the performance of the DTG, HRG, and FOG-based gyroscopes we selected as comparison technologies and enough to meet the ~0.1 °/hr performance target we estimated was necessary to match MWD performance. Indeed, for conventional oil and gas drilling, MEMS-based GWD services have recently become commercially available (Lowdon, 2017 and Weston, 2019). These MEMS-based GWD services can match or exceed MWD performance while providing added benefits associated with MEMS. These benefits include reduced measurement time since the gyro does not need to stabilize like a mechanical gyroscope and improved resistance to shocks since the MEMS sensing element is a relatively simple mechanical design with fewer parts than mechanical gyroscope technology.
Table 1: Vendors whose products we reviewed for navigation-grade gyroscopes. Data reported herein is from datasheets that are publicly available for download on the internet (performance data that is not publicly available on the internet is not reported).

<table>
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<tr>
<th>Vendor</th>
<th>Technology Referenced</th>
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<tr>
<td>Analog devices</td>
<td>MEMS</td>
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<td>Gyrodata</td>
<td>Drilling services</td>
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<td>Sperry Drilling</td>
<td>Drilling services</td>
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<td>KVH Industries</td>
<td>FOG</td>
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<tr>
<td>Murata</td>
<td>MEMS</td>
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<tr>
<td>Northrup Grumman</td>
<td>DTG</td>
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<td>Safran</td>
<td>MEMS, HRG</td>
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<td>Schlumberger</td>
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<td>Systron Donner</td>
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<td>Tronics/TTDK</td>
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The primary hurdle preventing usage of COTS MEMS gyroscopes in geothermal drilling is their fundamental temperature limit. None of the devices in Figure 4 are capable of functioning in a 300°C environment. In fact, we see about a 200°C temperature gap between state-of-the-art COTS MEMS gyroscopes and the geothermal drilling environment.

Figure 4: Performance and temperature capability of COTS devices we surveyed. (a) The best performing devices have bias instabilities approaching 0.1 deg/hr at room temperature. (b) Unfortunately, none of the devices can operate at 300°C. There is about a ~200°C gap between what is commercially available and what geothermal drilling requires for sustained operation at 300 deg C.
4. Design and Fabrication of the MRG

Our discussion of performance requirements and survey of the published MEMS devices has led to the discovery that no existing commercial MEMS gyroscope can reliably operate at 300°C for 1000+ hours while maintaining the sub-degree-per-hour accuracy needed for MWD. This is a critical technology that needs to be invented and developed.

To fill this need, GE Research has invented a new gyroscope design called multiple-ring gyroscope (MRG). MRG is an axisymmetric structure utilizing multiple concentric rings as the proof mass, as shown in Figure 5. Compared with disk resonator gyroscopes (DRG), the MRG has much lower mechanical stiffness which allows for higher drive amplitude, resulting in reduced angle random walk (ARW) noise. Compared to vibratory ring gyroscopes, the MRG has a higher performance entitlement due to its larger modal mass and improved sensitivity. Compared with tuning fork gyroscopes, the MRG is also inherently more robust against vibration and shock at downhole drilling conditions due to its uniformly distributed mass, axisymmetric structure and much higher frequency for the bending or translational modes.

Figure 5: GE MRG technology: (a) Conceptual view, (b) Finite element simulation to show the exemplary wineglass mode.

The operating principle of the MRG is based on Coriolis force which transfer the energy between two degenerated wineglass resonant modes (Figure 5). By design, these two resonance modes have the identical frequencies with the identical mode shape but spatially rotated from each other. In the operation, MRG is excited into the resonance in one of wineglass modes (drive mode). The vibration of the external platform will produce Coriolis force which transfers the energy from one of the wineglass modes to the other. The rate of rotation is therefore is determined by measuring the amplitude of the 2nd wineglass mode (sense mode) induced by the Coriolis force.

In principle, MEMS gyroscopes should withstand temperatures of 300°C since they are made from dielectrically isolated crystalline silicon which is stable at this temperature. However, in practice, high temperature in a well bore environment can adversely impact the MRG in several ways, which includes mechanical damping, thermal noise, and temperature induced stress on the MRG and package. To minimize performance degradation from these causes, the GE MRG
design has been optimized to ensure reliable 300°C operation. These innovations include optimizing ring geometry to reduce thermoelastic damping (TED) and optimizing the anchor location and the anchor attachment design to reduce anchor loss and improve MRG robustness against temperature-induced stress. One effective technique we used to optimize MRG geometry for 300°C operation is to space the frequencies of thermal mode and structural mode further away from each other. For a more detailed technical discussion of these design considerations and optimizations, see Lin, 2020.

Like other navigation-grade MEMS gyroscopes, the MRG requires highly specialized fabrication processes including thick silicon with high aspect ratio, vacuum sealing and high-precision, high-symmetry etching. GE Research has developed an all-silicon inertial MEMS process flow with these attributes called ‘Polaris’ process. As shown in Figure 6, the GE Polaris platform features thick silicon on insulator (SOI) with 20-200 um device layer, 30:1 high aspect ratio etch, wafer level vacuum sealing with through silicon via (TSV) technology.

Compared with the consumer-grade and automotive-grade gyroscopes, navigation-grade gyroscopes often start at a much lower volume demand and require more iterative steps of process and design optimization. GE Polaris strives to provide the simplest inertial MEMS flow with wafer-level vacuum sealing and TSV capabilities, making it suitable for quick prototyping and low-to-mid volume production. The development of GE MRG is a good example to showcase how the Polaris flow, as a platform technology, can accelerate the innovation and adoption of navigation-grade inertial sensors.
5. MRG Component Validation

We have fabricated the MRG and are now completing component validation.

Figure 7a shows the Allan Deviation plot for the MRG mounted onto the test board. The MRG was fabricated by the GE Polaris process with wafer-level vacuum seal and TSV with a die size of 10mm x 10mm x 0.5mm. The GE MRG under test demonstrate an ARW of 0.003°/√hr and in-run bias instability of 0.01°/h at room temperature, which is considered as one of best performing gyroscopes ever achieved by the wafer-level sealed MEMS gyroscope. The ARW from test also agrees well with the prediction from our simulation, validating our design approach and the capability of Polaris process for precise fabrication of navigation grade gyroscopes.

Figure 7: Allan deviation measurements. (a) Allan deviation at room temperature shows bias instability of 0.01°/hr and angle random walk (ARW) of 0.003°/√hr. This level of performance is an order of magnitude better than what is commercially available today. (b) ARW versus temperature over the range 25 - 225°C. The increase in ARW is expected because we have not yet implemented temperature compensation.

Figure 7b shows the ARW for a GE MRG test device measured from 25 - 225°C operating temperature (using the test board with localize heating method). The MRG remains fully functional across the whole temperature range. The increase in ARW with temperature is expected since we have not yet implemented temperature compensation.

The sealed MRG is further characterized to 500°C to check the device integrity. Figure 8 shows the Q-factor variation for a wafer-level sealed MRG up to 500°C. Two high temperature cycles were performed to show the device had no degradation and the device sealing integrity has not been compromised. This stress test at 500°C gives us confidence the package will have good reliably when continuously operated at the substantially lower temperature of 300°C.
Finally, we completed demonstrations where we used the MRG to sense rotation rate. In Figure 9a, we show the MRG output as it is being rotated on a rate table for temperatures spanning 25 - 300°C. Although there is the expected decrease in sensitivity due to reduction of quality factor and lack of temperature compensation, the MRG clearly senses rotational movement at 300°C. Figure 9b shows the sensitivity (scale factor) of the MRG as a function of temperature. The baseline sensitivity was determined from the data in Figure 9a, and the improved sensitivity was determined after device optimization. Device design and control enhancements have been undertaken to improve the device drive capability and enable electrostatic tuning of critical device parameters such a frequency split between drive and sense modes, and quadrature nulling. As can be seen in Figure 9, the enhancements have resulted in the device sensitivity enhancements of greater than two orders of magnitude over the prior baseline data.
The high temperature validation data of the MRG demonstrates the integrity and capability for MRG to be used in 300°C operation. Our test data suggests the MRG will have quality factor of approximately 5,000 at 300°C. The control circuit has enough tuning range so that MRG can be maintained at the optimal 1um drive amplitude. According to our initial assessment, the ARW will degrade by <3 times when going from room temperature to 300°C, resulting in an expected bias instability <0.1%/hr. Considering the transfer functions in Figure 1 and Figure 3, we expect that at 300°C the MRG is capable of an azimuth finding uncertainty of approximately 0.5° (1σ) and a well path uncertainty that matches the performance of MWD as used by the oil and gas industry.

6. Work in progress and next steps

For MRG component validation, we are improving our ability to test and characterize the MRG at elevated temperatures. We are adding temperature compensation to the control electronics running the MRG. We are also rapidly expanding our high temperature characterization capability for testing at 25-300°C. We are working towards an automated, 300°C gyrocompassing test where the MRG will repeatedly determine azimuth by sensing earth rate. By completing many repeated measurements (e.g., 25), we will characterize the accuracy and uncertainty in this MRG’s azimuth measurement at 300°C. For ASIC development, we have completed our designs and are preparing to begin fabrication of component devices. This ASIC development will be discussed in a future update. In Phase 2 of this program the MRG and ASIC will be integrated on a high temperature capable substrate and used for performance characterizations at 300°C, including 1,000 hour lifetime and reliability testing.

Conclusion

To improve the efficiency and effectiveness of drilling unconventional geothermal wells, GE Research is developing a new MEMS gyroscope for 300°C MWD. This new gyroscope, called an MRG, is designed and optimized for high temperature operation. Component testing is in progress and the MRG is showing excellent performance. The transducer is functional from 25°C to 500°C, and we demonstrated navigation grade performance with bias instability and angle random walk values of 0.01°/hr and 0.003°/√hr at 25°C. We have shown the MRG is functional at 300°C, sensitive to rotational movement, and performing as expected given we have not yet compensated for temperature changes in the control algorithm. We are currently expanding our high temperature characterization capability and are well positioned to integrate this gyroscope with a custom ASIC for 300°C MWD.

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