Current and Future Performance of Si-MEMS Quad Mass Gyro (QMG) System

Flat is not Dead

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## Current Status of SoA MEMS Gyros

<table>
<thead>
<tr>
<th>MEMS gyro parameter (SoA production IMUs)</th>
<th>Tactical grade</th>
<th>Inertial / azimuth grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias in-run, °/hr</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>Bias composite, °/hr</td>
<td>10</td>
<td>0.01</td>
</tr>
<tr>
<td>ARW, °/√hr</td>
<td>0.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Rate Noise, °/hr/√Hz</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>Scale factor, ppm</td>
<td>&gt;100</td>
<td>1</td>
</tr>
</tbody>
</table>

100x improvement in MEMS gyro performance required for Navigation / Azimuth grade applications.

NG LITEF  
Honeywell  
ADI  
Sensonor  
Goodrich

Approved for public release
## Two Classes of Coriolis Vibratory Gyros

<table>
<thead>
<tr>
<th>IEEE STD 1431</th>
<th>Class I</th>
<th>Class II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal symmetry (not axial)</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Whole angle, self-calibration</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>MEMS implementation</td>
<td>lumped masses</td>
<td>ring, disk, (shells in R&amp;D)</td>
</tr>
<tr>
<td>Angle gain, drive amplitude</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Modal mass, decay time (Q)</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Defining examples</td>
<td>Draper/ Honeywell</td>
<td>BAE/ AIS/ Goodrich/ UTC</td>
</tr>
</tbody>
</table>

Tactical grade HG-1930 and SiIMU02 are dominant production SoA MEMS IMUs since ~2000.

**Revolutionary potential**: mode-symmetric tuning fork with low ARW of Class I and good stability of Class II.
Quad Mass Gyro (QMG)

- 4 tines, 20 levers
- Symmetry, balance

- No anchor loss, TED limited $Q > 1 \ M$
- Measured $\tau = 3 \ \text{min}$ and $Q > 1 \ M$

Quad Mass Gyro: Class II tuning fork CVG with $Q > 1 \ M$, whole angle, and self-calibration.
Resonator Alone Does Not Gyro Make

- Rate mode, whole angle, mode reversal, carouseling
- All closed loop

Stand alone, turn key gyro suite; DARPA PALADIN compatible. Adaptable to other CVGs through analog card interchange.

QMG in cer. DIP (no getter, Q=1 k)
USB port to PC
RS 232 to PC
Gyro buffer card
Motherboard (DSP, FPGA, power, and communication)
PALADIN connector
Whole Angle QMG Performance

- QMG without getter
- $Q = 1\ k, \ \tau = 0.1\ sec$

1 hr at 100 °/s for .3E6 °
All closed loop operation

Whole Angle with 3 PPM error demonstrated on QMG (despite low Q package without getter). 18,000 °/s range.
Rate Mode QMG Performance

- QMG without getter
- $Q=1 \, k$, $tau=0.1 \, sec$
- $1/2 \, month$ in-run experiment
- All closed loop with self-cal.

Modified Allan deviation ($^\circ$/hr) vs. time (s)

- 1 $^\circ$/hr or 0.2 PPM @10 s
- 0.5 $^\circ$/hr or 0.1 PPM @30 s
- 0.2 $^\circ$/hr (0.04 PPM) from mins to weeks

0.2 $^\circ$/hr or 0.04 PPM bias stability over weeks.
Full scale of 1350 $^\circ$/s, dynamic range >145 dB.
Angle Random Walk $\propto$ Mass$^{-1/2} \times$ (Frequency $\times$ Q-factor)$^{-1/2}$
**Navigation Grade QMG Capability**

**Q=1 M QMG with getter packaging beats navigation grade ARW of <0.05 °/hr/√Hz** with room for more improvement.

- 2.5 kHz, (8 mm)$^2 \times 100$ um, AG=0.75, A=1.5 um

- **QMG no getter (test & simulation)***

- **QMG w/ getter (simulation)***

Approved for public release
Quad Mass Gyro (QMG) Conclusions

**QMG** - a clear path to Navigation / Azimuth grade Si-MEMS

- Ultra-low dissipation due to mechanism design
- Mode symmetry enables whole angle, self-cal.
- Wide range in rate mode due to large capacitance
- Mature silicon technology, no exotic fabrication

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