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Micromachined vibrating gyroscopes

Jan Söderkvist

Colibri Pro Development AB
Torgnyvägen 48, SE-187 76 Täby, Sweden
Phone: +46-(0)8-510 116 49Fax: +46-(0)8-510 116 15
E-mail: colibri@prodev.se

ABSTRACT

Angular rate sensors are often used in combination with accelerometers. Both sensor types are based on inertial forces and they do not require direct contact with the surrounding. However, angular rate sensors are much more difficult to design and fabricate due to them using large ratios of vibration amplitudes which makes them very sensitive to various error sources. This is one reason why micromachined rate sensors are not frequently found on the market, despite a large interest from the automotive and military industry. Nevertheless, vibrating angular rate sensors have a large potential for such applications. A general description of vibrating angular rate sensors and some design aspects is given below, together with a more detailed description of a quartz angular rate sensor. This quartz sensor is currently developed for mass-production in collaboration with a major European automotive industry.

Keywords: Angular rate sensors, gyroscopes, micromachining, piezoelectricity, quartz, vibrations, resonators, applications, sensor principles, design aspects

1. INTRODUCTION

Accelerometers and angular rate sensors both measure inertial forces. For accelerometers, the output from the sensor element is a signal proportional to the applied linear acceleration, and for vibrating angular rate sensors, a signal proportional to the applied angular velocity.

Micromachined accelerometers in silicon and quartz are commercially available. These inertial sensors show that micromechanical structures are well qualified for today's demands for inexpensive, small and reliable sensors. Micromachining is therefore likely to be useful also for meeting the emerging need in many automotive and consumer applications for small and inexpensive angular rate sensors.

Conventional gyroscopes, based on conservation of angular momentum of a spinning rotor, are too expensive, too large, and have a too short lifetime, for most new applications. This is also true for fiber and laser gyroscopes, although their performance can be excellent. Thus, there is a need for a new class of, preferably micromachined, gyroscopes.

At present, no cheap micromachined angular rate sensor exists on the market. Available quartz rate sensors are currently too expensive since they are developed for military applications. Silicon rate sensors are not yet available, mainly due to them being more complex to design.

2. APPLICATIONS

2.1. Automotive applications

The advancement of safety and electronic systems for cars has made inertial sensors important components. Unfortunately, the lack of reliable and inexpensive rate sensors has led to most safety systems, including airbag and restrain systems, not responding to accidents involving mainly rotations of the vehicle.

AREA	EXAMPLE OF APPLICATIONS	RANGE [°/s]	ACCURACY [°/s]
Automotive safety reliable, inexpensive, rough environment, lifetime	improved controls for airbags	200	10
	anti-collision systems	100	1
	active suspension	50	2
	anti-skid	100	0.5
Consumer inexpensive, small, lifetime, low-power	free-space pointers for computers	100	1
	remote control devices (TV-controls)	100	2
	video camera anti-jitter compensation	50	0.5
	navigation (complement to GPS)	50	0.5
	toys and sports equipment	varies	varies
Industrial reliable, small, rough environment	machine control	10	0.01
	angular vibration measurements	varies	varies
	attitude control of flying objects	20	0.02
	automatic guided vehicles	50	0.2
	stabilized platforms	20	0.2
	robotics	10	0.01
Medical reliable, small, low-power	monitoring of body-movement	100	1
	vibration diagnostics	50	0.5
	controls for paralyzed patients	100	2
	surgical instruments	20	0.1
	wheel chairs	50	0.2
Military reliable, small, rough environment	new weapon systems	-	-
	smart ammunition	-	-

Table 1. *New applications that need small or inexpensive micromachined inertial sensors, including estimates of typical required performance*[3].

Another safety systems for which angular rate sensors will become important is anti-skid systems. Here, the rotation speed of the wheels, steering wheel position, and accelerometers, do not give sufficient information if all wheels are skidding, e.g., after a too rapid turn. Additional information is needed of how the car rotates around its center of gravity.

Motion control, like active and adaptive suspension for improved comfort and safety, is also a coming application for angular rate sensors. Such systems have successfully been tested in sports cars.

The satellite based GPS-system is important for automotive navigation. However, updates of the position can only be obtained at a few minutes interval due to ground interference from tall buildings, mountains, tunnels, etc. Thus, there is a need for an additional navigation system that can give the position in-between the GPS-updates in densely populated areas.

The use of micromachined angular rate sensors in automotive applications will increase rapidly already this century.

2.2. Consumer applications

Consumer products rapidly increase in complexity. Despite this increase in sophistication level, great effort is spent on increasing the user friendliness due to this giving an excellent competitive edge. It will be natural to include inertial sensors if they are inexpensive. An existing example is the gyro-based anti-jitter compensation used in ordinary video cameras[1]. Their, the rate sensor signal is used to either stabilize a mechanical platform within the camera, or to move the CCD-generated image electronically.

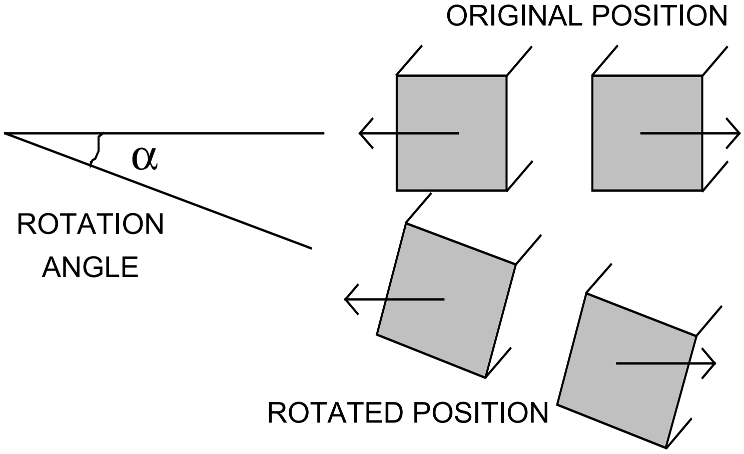

Figure 1. *This cross-section view of a tuning fork illustrates how a vibrating angular rate sensor works. A vibration component out of the plane of the tuning fork is generated when the structure is rotated, due to the conservation of linear momentum.*

New free-space pointers will open the ground for advanced remote controls for, e.g., audio visual equipment, virtual reality, and environment control in ordinary houses. Small vibrating angular rate sensors can successfully be used in new small ergonomic computer mice that detect head movements. This makes it possible to always keep the hands on the keyboard, and it increases flexibility for disabled people.

In addition, the largest application areas for inexpensive angular rate sensors might turn out to be toys, games and sports equipment. Only the imagination limits the number of applications in these areas.

3. SENSOR PRINCIPLES

3.1. Accelerometer-based

The simplest alternative for low-performance applications is to derive the angular velocity signal from two accelerometers separated a distance d. The angular acceleration is then given by (acceleration_1-acceleration_2)/d.

Unfortunately, using accelerometers means poor zero-point stability since the angular velocity is obtained by time-integrating the angular acceleration. The errors will be integrated at the same time as the useful signal. The zero-point stability is further degraded by performance differences between the two accelerometers, for instance due to temperature differences.

3.2. Conservation of momentum

Better accuracy is reached by introducing a reference motion that enables the use of conservation of momentum (cf. Foucault's pendulum). An angular rotation will then generate Coriolis forces (inertial forces) whose properties are partly related to those of the reference motion.

Conventional gyroscopes and angular rate sensors are based on the conservation of angular momentum of a massive spinning rotor. This alternative is not suitable for micromachining since friction restricts lifetime, unless a quasi-vibration is used (QVS, se next section).

Conservation of linear momentum of a vibrating structure is a more promising alternative for micromachined structures. Such structures can withstand rough environments for long periods of time, implying a lifetime not limited by the sensor-element itself.

3.3. Vibrating rate sensors

A vibration strives to stay in its original plane of vibration according to Newton's law. Thus, a rotation that changes the orientation of this plane will generate inertial forces that tries to return the vibration back to its original vibration plane. A vibration component perpendicular to the original vibration is then created, as shown in Figure 1. The amplitude of this rotation-induced vibration is proportional to the speed of rotation.

An alternative to the use of a linearly bending vibrating structure is to use quasi-vibrating structures (QVS). Here, a torsional vibration that forms part of a rotation is used. This type of rate sensor is also suitable for micromachining.

Tracing a point on the structure reveals a difference between the two alternatives. For the quasi-vibrating structure, the motion is parallel to the axis of the applied rotation, while it is perpendicular for the vibrating structure.

4. DESIGN ASPECTS FOR THE SENSOR ELEMENT

A vibrating angular rate sensor is a complex sensor to design (Figure 2). In fact, performance is to a lesser degree controlled by the scale factor and resolution. Much more important is how well and stable the error sources are suppressed. In addition, there are technological questions that will not be addressed here.

4.1. Amplitude ratio

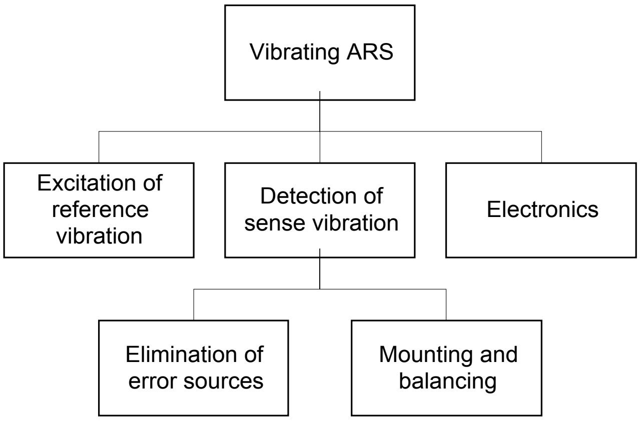

Figure 2. *Building blocks of an angular rate sensor.*

All vibrating angular rate sensors use two, preferably perpendicular, vibrations (rotations for quasi-vibrating QVS) whose momentum are conserved by inertial forces. One is the reference vibration. The other is the sense vibration, whose amplitude is proportional to the applied rotation.

The amplitude ratio is unfavorable as illustrated by the following expression for a cantilever beam with almost square cross-section:

$$\frac{\mathrm{Amp}_{\mathrm{sense}}}{\mathrm{Amp}_{\mathrm{ref}}} = \frac{\Omega}{\pi \cdot f_v} \cdot \left[\left(1 - x^2\right)^2 + \left(\frac{x}{Q_s}\right)^2 \right]^{-0.5}$$

where Ω is the applied angular velocity, Q_s describes the damping of the sense vibration, and $x=f_v/f_s$. Normally, the vibration frequency, f_v, equals a resonance frequency, f_r, of the reference vibration (not f_s of the sense vibration). This results in an amplitude ratio as small as 15 ppm for a 100 Hz bandwidth and a rotation of 1 °/s[3]. Thus, the sense amplitude is roughly ½ an atomic radius for a 10 µm reference vibration, at 1 °/s. This explains mostly the large sensitivity to error sources.

4.2. Resonance frequencies

Using resonance frequencies increases the vibration amplitudes, and thus the response. However, an exact frequency match ($f_r=f_s$) is difficult to maintain. This difficulty is worsened by aging and temperature drift, as well as by imperfections in the mounting and by the presence of a mechanical coupling. Also, equating the two resonance frequencies gives a very slow response time for the system that necessitates active feedback of the sense vibration. The two resonance frequencies are therefore normally separated slightly to reduce this source of stability error and to increase the response time sufficiently.

4.3. Geometries

The large difference in vibration amplitude between the two vibration directions results in demanding requirements on the mechanical design of the sensor element:

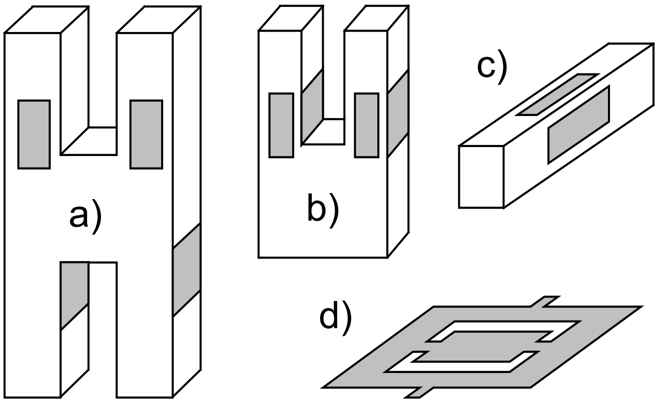

Figure 3. *Some suitable geometries for micromachined vibrating rate sensors: a) double ended tuning forks (Systron Donner[4]), b) single ended tuning forks (Colibri[5]), c) beams (General Electric[6] and Murata[1]), and d) QVS (Draper[7]).*

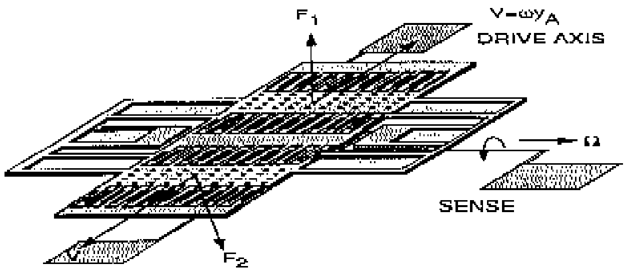

Figure 4. *Comb shaped electrostatically excited and capacitively detected silicon angular rate sensor element[8,9].*

- the reference and the sense vibrations must be very well isolated from each other, i.e., no mechanical coupling is allowed between them,
- vibrational inactive mounting areas must be used to reduce uncontrolled aging and temperature drift induced by the surrounding,
- a stable and inert material should be used for the sensor element, and
- stray signals must be kept at a minimum.

The mounting aspect explains why tuning forks and other well balanced structures are frequently encountered in vibrating angular rate sensors (Figure 3). Comb-based structures are often used for electrostatic excitation and capacitive detection (Figure 4). This enables larger capacitances and vibration amplitudes.

4.4. Material

The choice of material for the sensor element is essential. High requirements on the zero point stability highlights two crystalline materials: quartz with piezoelectric excitation and detection, and silicon with electrostatic excitation and capacitive detection.

Micromachining of mono-crystalline materials gives structures with long lifetimes, high fracture strength, and high Q-values. If the mechanical resonance frequencies are chosen high, and if the vibration modes are symmetric and well balanced, then the structures will withstand tough environments, survive high shock levels and have virtually no vibration sensitivity.

For silicon, existing semiconductor manufacturing equipment may be used to included integrated electronics on the sensor element. The major drawback with silicon is that it is not piezoelectric. Combined solutions, e.g., ZnO-films on silicon, degrades the Q-values, and do not offer the necessary material stability.

Piezoceramics offer high piezoelectric activity. However, the Q-value is low and the aging and temperature dependence of the material parameters is high. This may explain why rate sensors made from bulk piezoceramics are only partly successful on the market.

4.5. Excitation of the reference vibration

Piezoelectric excitation offers a suitable means for exciting the resonant vibration. The resonance frequency can be found by monitoring the current through the electrodes. At resonance, there is a rapid phase change and increase in the piezoelectrically deflection-induced current.

Electrostatic activation with capacitive detection, using comb- or plate-shaped structures, is one of the better alternatives for silicon sensor elements. A drawback is that this method relies on the stability of external surfaces that do not participate in the vibration. Thermal excitation with piezoresistive detection can also be used for exciting the reference vibration.

4.6. Detection of the Coriolis-induced vibration

Only a few means for detecting the subatomic sense amplitude exist, e.g., piezoelectric and capacitive means. For small amplitudes, piezoelectric detection (pA currents for quartz) is in general more accurate than capacitive detection (aF capacitance changes). However, capacitive detection and comb- or plate-shaped structures is one of the few useful alternatives for silicon.

The piezoelectric effect enables selected vibration modes to be detected by choosing the electrode configuration properly. Some error sources generated by the large reference vibration can then be suppressed without the influence of external surfaces.

The resonance frequency of the Coriolis force equals that of the reference vibration. Using this fact in the electronic extraction of the rate signal reduces the vibration sensitivity to sufficiently small levels, if all mechanical resonance frequencies of the sensor element, including the package, are well outside the frequency range of the external vibrations. Symmetric electrodes that detect only anti-symmetric vibration modes aids in further suppressing external disturbances.

Piezoresistivity can be used for some materials, e.g., for silicon, but with reduced performance. Optical detection is, if feasible, too expensive. Inductive detection is better suited for macroscopic dimensions.

5. SYSTEM ASPECTS

The sensor element constitutes only one part of an angular rate sensor. In some aspects, it is even more important to consider the design of the surrounding parts. For instance, performance can be degraded more by an erroneously designed electronics or mounting than by a sensor element that is not optimized.

5.1. Electronics

Basic functions of the electronics are (Figure 5):

- Excite reference vibration
- Detect sense vibration
- Extract rate sensor information
- Adjust signal levels
- Protect (external disturbances, supply voltage variations, ESD, …)

The reference vibration should preferably be excited at a mechanical resonance frequency and be keep at a constant vibration amplitude. The extraction of the rate sensor information is facilitated by that its frequency equals that of the excitation signal, and that it has a known phase relative this signal.

In order to reduce the effect of the unavoidable error sources, the electronics must be design with phase stability as the key design criteria. This means designing the electronics for MHz-frequencies although the mechanical vibration frequency is in the kHz-range. It also means that the electronics must be developed specifically for each sensor element design.

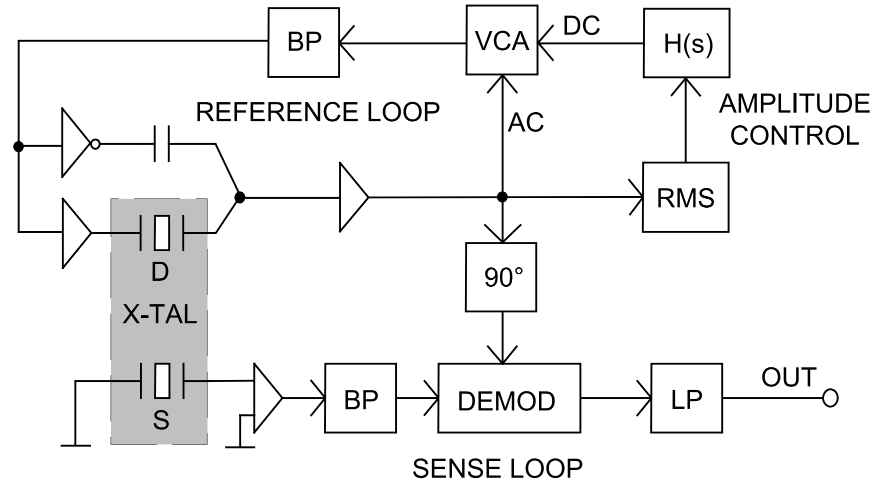

Figure 5. *Block diagram of the electronics.*

A miniaturization of the electronics could improve performance by reducing stray signals and enabling special designed circuit solutions.

5.2. Mounting and packaging

Extra care must be taken in the design of the mounting of the sensor element due to the large difference in vibration amplitudes. A badly designed mounting can seriously affect performance since resonance frequencies, Q-values and some error sources are sensitive to changes in the surrounding.

A high Q-value of the mechanical vibrations, e.g., obtained by a proper mounting and using vacuum, is advantageous. This results in more pronounced resonance frequencies, a reduced effect of stray signals, and a more stable phase of the sensor signal. However, this makes the packaging difficult, especially if vacuum is to be guaranteed for the life-time of the sensor.

Packaging and mounting are topics so important and complex that their treatment does not fit into the scope of this presentation.

5.3. Error sources

In the ideal case, optimizing the scale-factor and the resolution is sufficient. It is then found that the sensor can be fabricated with micromachining and that several material and geometry combinations give sufficient performance. Thus, the ideal angular rate sensor can be treated as a standard micromachined sensor.

However, the small sense amplitude relative the reference vibration causes serious complications. Even the slightest unsymmetry, temperature drift, aging, stray impedance, etc., may cause failure to meet the specification. An optimization of the sensor system is almost entirely controlled by how well the error sources are suppressed both mechanically and electrically.

Most error sources will affect the zero rate offset (ZRO) independent of material choice and geometry. As an example, electric feed-through in phase with the rate signal can be substantial for piezoelectric rate sensors. A 0.1 pF stray capacitance can result in an erroneously ZRO signal that corresponds to several 100 °/s for the quartz angular rate sensor presented below. Electric compensation and careful layout can compensate for most of this error.

Vibration energy can be transferred from the reference vibration to the sense vibration if the two vibrations are mechanically coupled. The resulting sense vibration can result in a larger ZRO than the ZRO due to electric feed-through. Fortunately, this error signal is roughly out of phase with the Coriolis induced signal. One way of reducing this error is to mechanically

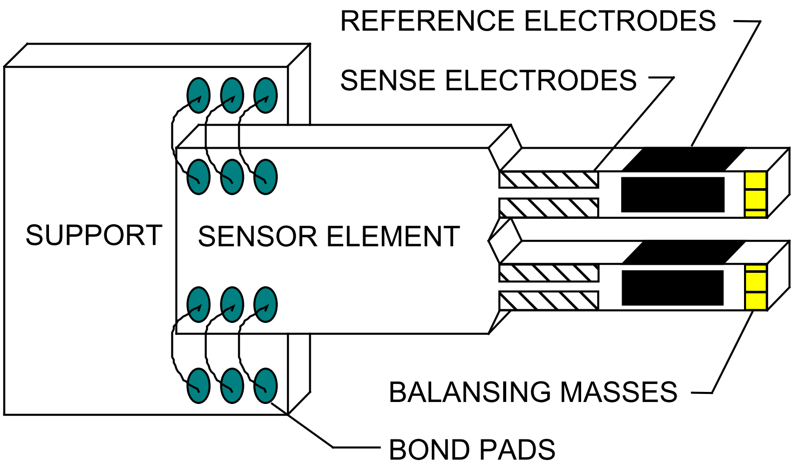

Figure 6. *Piezoelectric sensor element. Compromises must be made for the location of electrodes for excitation and detection.*

balance the sensor element by adding or taking away material on selected areas. Balancing can also be used to obtain the desired scale factor by adjusting the resonance frequencies.

A third serious source of error is an inferior isolation between the vibrational active areas and the mounting. It has been observed that uncontrollable mechanical stress in "stable" surrounding materials can affect most characteristics of the sensor element, like the mechanical coupling, the Q-value and the resonance frequencies. Reducing this effect by introducing a weak mounting degrades the ability of the sensor to withstand the shock-levels encountered during manufacturing and transportation, and reduces the Q-value in an undesired way if not properly designed.

An understanding of the error sources can lead to improvements in the electronics, for instance by adapting the electronics to the small signal-to-ZRO ratio. Active cancellation early in the electronics can be used to reduce the largest components of ZRO. This puts less strain on the remaining electronics and reduces the risk of saturation.

6. A QUARTZ ANGULAR RATE SENSOR

An angular rate sensor based on a single ended tuning fork has been developed by Colibri Pro Development AB. The quartz sensor element in Figure 6 is similar to ordinary batch-processed watch crystals that are mass-produced at a production cost of less that a few tenth of a dollar. One difference is that thicker wafers are used to increase the detected rate signal. Up to fifty sensor elements may be fitted on a single 1½×1½ inch quartz wafer (cf. 200-300 for watch crystals). Thicker wafers increase the detected rate signal, but reduce yield (etch damages) and the number of sensors per wafer.

Two sets of electrodes are used. The reference electrodes create the electric field that activates the in-plane flexural reference vibration. The large Q-value caused increase in amplitude at resonance implies that activation voltages larger than a few volts may lead to mechanical fracture. The low drive level, below 10 mW, results in no thermal gradients or stress.

The sense electrodes detect the 50 pA/°/s current generated piezoelectrically by the Coriolis induced out-of-plane flexural sense vibration. The noise of the preamplifiers is well below this value.

Measured values at room-temperature include (Figure 7) resolution <0.1°/s, noise <0.3°/s, non-linearity <0.5%, hysteresis <0.1°/s, start time <1s, and virtually no cross-axis or vibration sensitivity. This suffices for many new applications.

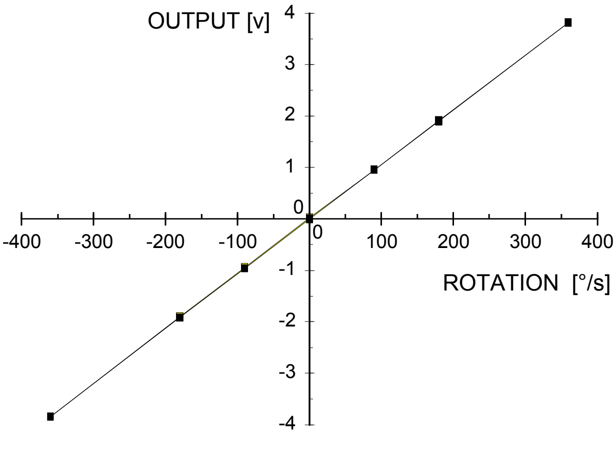

Figure 7. *Measured performance.*

The ZRO-stability is better than 0.5°/s/hour, at constant temperature. The main difference at other temperatures is a repeatable change in the ZRO. Self-heating of the electronics induced a 0.7°/s ZRO-drift at power-up during the first 15 minutes, with a time constant of 3 min.

7. DISCUSSION

Many new applications that need small and inexpensive inertial sensors exist, especially in the automotive and consumer fields. The size and cost of gyroscopes have previously made it difficult to consider gyroscopes for these applications. New sensor concepts and technologies, including micromachining, are beginning to overcome these obstacles.

Performance of the presented quartz angular rate sensor is sufficient for adopting the sensor for mass-production for automotive applications. This ongoing development will concentrate on meeting the specification over full temperature range, to reducing the sensitivity to variations in a production, and to obtain the correct sensor system solution for low production costs.

One of the most difficult performance parameter to fulfill for any vibrating rate sensor is the zero point stability. In order to overcome this, it is essential that:

- error sources are suppressed both in the sensor element and in the electronics,
- mechanical balancing of the sensor element is used, and
- active control loops in the electronics are used to compensate for aging, and to facilitate handling during fabrication.

If the DC-value of the sensor response is of less importance, then an auto-zeroing can be used. This can drastically relax the design work.

The production cost of micromachined gyroscopes is controlled by electronics (ASIC), packaging, balancing and assembly, and not only by the sensor element. More care must be taken in the manufacturing of silicon-based rate sensors than for quartz-based, due to silicon angular rate sensors being more complex on the system level. This is compensated for by an expected lower cost of the silicon sensor element, caused by larger wafers and more well-developed and accessible manufacturing equipment. One guess is that quartz-based angular rate sensors will be less expensive, except for low performance applications, for which silicon-based angular rate sensors will dominate. The question is where the borderline in performance will be.

A standard 14-pin metallic package, containing the sensor element and an ASIC, is suitable for gyroscopes with low and moderate performance. Higher performance may need a larger package.

An observation to conclude this presentation: House-flies use vibrating organs for obtaining stability in pitch[9]. The effort is now to recreate this 200 million years old invention — with the help of micromachining.

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