Micromachined inertial sensors: the state-of-the-art and a look into the future

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Introduction

Until recently inertial sensors were restricted to applications such as military and aerospace systems in which the cost of these sensors was of little concern. The emergence of micromachining has generated the possibility of producing precision inertial sensors at a price which allows their use in cost-sensitive consumer applications.

A variety of such applications already exists, mainly in the automotive industry for safety systems such as airbag release, seat belts control, active suspension and traction control. However, the majority of products are currently in their early design stage and the range of applications is only limited by one's imagination. Examples include anti-jitter platform stabilisation for video-cameras, virtual reality applications with head-mounted displays and data gloves, GPS back-up systems, shock-monitoring during the shipment of sensitive goods, novel computer input devices, electronics toys and many others.

Clearly micromachined sensors are a highly enabling technology with a huge commercial potential. The requirements for many of the above applications are that these sensors are cheap, can be fitted into a small volume and their power consumption must be suitable for battery-operated devices. Micromachined devices can fulfil these requirements since they can be batch-fabricated and advantages similar to those for standard integrated circuits are envisaged.

Micromachined inertial sensors have been the subject of intensive research since Roylance *et al*[1] reported the first micromachined accelerometer in 1979. Since then many authors have published work about various types of micromachined accelerometers and - more recently - gyroscopes[2,3]. In many of the above-mentioned applications information about the angular and linear motion of a body in its six degrees of freedom is required, hence it is desirable to combine accelerometers and gyroscopes in one sensing unit. So far research has mainly focused on the implementation of devices which measure either linear or angular motion.

The requirements for these inertial sensors vary drastically with their intended applications. *Figure 1* gives an overview of the main performance requirements for accelerometers and gyroscopes for various applications.

Micromachined accelerometers

Accelerometers usually consist of a suspension system and a proof mass whose deflection provides a measure of the acceleration. These devices can usually be classified by the fabrication technology, the method of transduction from mechanical to electrical domain and the type of control system used. Two fabrication processes - bulk-micromachining and surface-micromachining - are dominating; both rely on micromachining standard silicon wafers.

Bulk-micromachining uses the full thickness of a wafer and is a subtractive process. Silicon is removed by wet- or dry-etching techniques and forms a proof mass and a suspension system. A typical example is shown in *Figure 2* and described in detail in

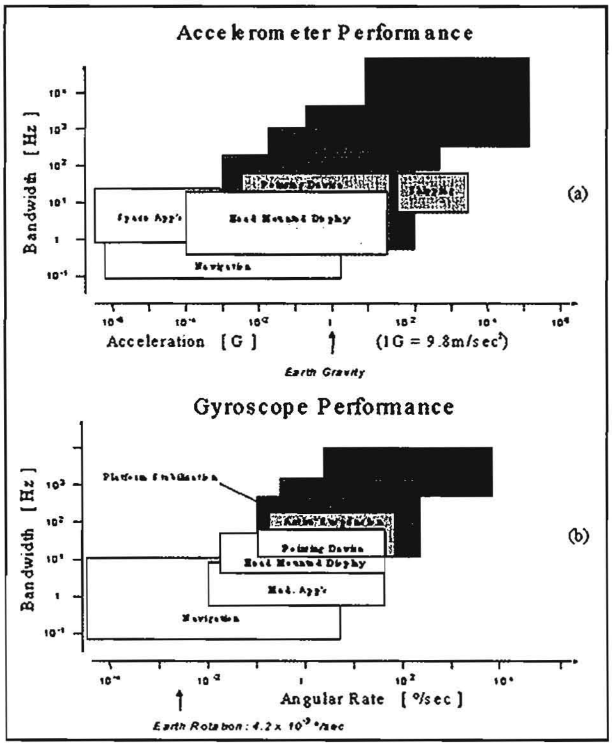

Figure 1: Overview of applications and required performances for micromachined inertial sensors: (a) accelerometers; and (b) gyroscopes.

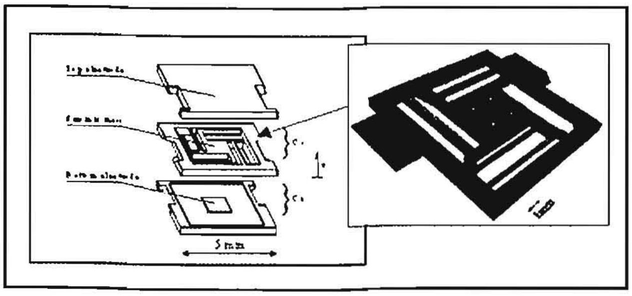

Figure 2: A bulk-micromachined accelerometer with capacitive signal pick-off.

reference[4]. Often these sensors consist of a sandwich of several wafers (either silicon or Pyrex) bonded together to provide electrical contact and form an enclosure for the proof mass. Bulk-micromachining was used in earlier devices and most commercial accelerometers are fabricated in such a way. This technology is not very suitable for monolithic integration; it is often used in conjunction with a separate integrated circuit in the same package[5], or even with discrete electronics.

A technology which is suitable for integrating the electronics and the mechanical structures on the same chip is surface-micromachining[6]. This is an additive process in which thin films of typically poly-silicon and silicon-oxide are grown on a wafer. The oxide acts as a sacrificial layer and is removed by a release step by a wet-etchant such as HF. This results in free-standing beams and plates. The sensing elements are typically an order of magnitude smaller than bulk-micromachined devices (in the range of several hundred µm). This technology is compatible with a standard CMOS process and has led to monolithically integrated devices. A commercial range of sensors is available from Analog Devices[7]; the first device was the ADXL05 which has a 0.5 mg/rt-Hz noise floor with a ±5g dynamic range.

Another characteristic is the type of transduction from the mechanical to the electrical domain by measuring the deflection of the proof mass. The two most commonly used ones are piezo-resistive and capacitive sensing. Alternatives are piezo-electric sensing[8] (mainly for high-frequency applications), tunnelling current sensing[9] (very sensitive but of increased complexity) and optical methods[10]. In this paper only the two first methods will be discussed.

Piezo-resistive detection was used in the first sensors and is still used in many commercial devices (e.g. by SensoNor[11]). Piezo-resistors can easily be diffused into the bending beams with which the proof mass is suspended; it provides DC response and results in low-impedance resistors. Resistor changes can be detected relatively easily by standard bridge techniques. The drawbacks are that the output level is not very high (a typical value is 100 mV for a 10V drive), the temperature coefficient is relatively large and thermal noise is intrinsically generated in the resistors. Typical performance figures for these devices are a sensitivity of 1-3 mV/g, 5-50 g dynamic range and an uncompensated temperature coefficient of <0.2 %/°C.

Mainly due to these drawbacks, more modern devices use capacitive detection. Here differential capacitors are often formed by using the proof mass as the common middle contact of a capacitive half-bridge. For small deflections the differential change in capacitance is proportional to the deflection of the proof mass and can be converted into a voltage by a charge amplifier and a synchronous demodulation technique. This approach has established itself as the prevailing technique among most commercial and prototype devices.

The last classification criteria is the type of control system employed. Generally one can distinguish between open- and closed-loop operation. In the latter a feedback force is generated on the proof mass which counterbalances the inertial force. The required force provides a measure of the input acceleration. Most commercial devices are open-loop; however, force-feedback has a range of advantages such as an increase in bandwidth, linearity and dynamic range. The drawback is increased complexity of the electronics and hence increased cost.

For high-performance applications, however, force feedback is essential. A potentially navigation-grade accelerometer[12] is probably the highest-performance micromachined accelerometer to date. Typical performance figures are a resolution in the 1µg range, a bandwidth of better than 100 Hz and a temperature sensitivity of <200 ppm/°C. A further advantage of capacitive sensing is that the capacitors can be used both for sensing and electrostatic feedback. These signals are multiplexed in either the frequency domain or the time domain. A problem with electrostatic force-feedback is that electrostatic forces are always attractive and have a non-linear dependency on voltage and the gap between the electrodes. Usually a differential arrangement is used to linearise this relation-

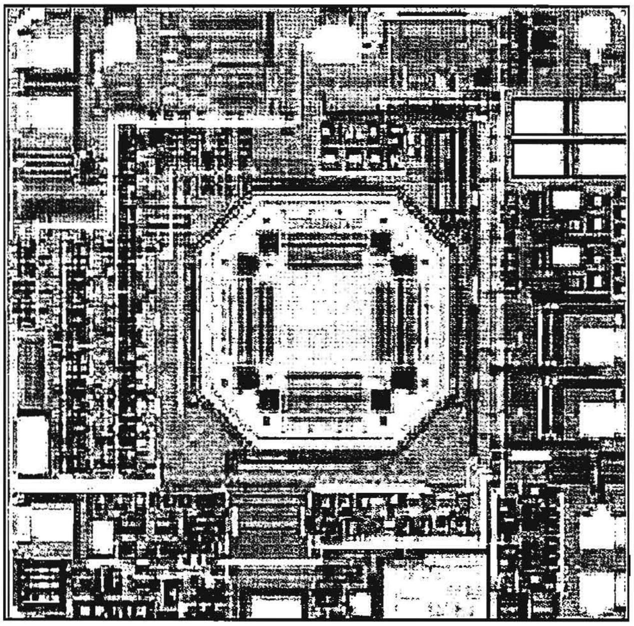

Figure 3: An ADXL202 fully integrated, surface-micromachined 2g dual-axis accelerometer, available from Analog Devices.

ship and to generate a force proportional to displacement. Either analogue or digital feedback can be used: the former requires a bias voltage and is potentially prone to electrostatic pull-in; whereas the latter incorporates the sensing element in an electro-mechanical sigma-delta modulator loop[13,14]. This approach - which has the advantages of improved system stability and of a direct digital output signal being produced in the form of a pulse-density modulated bit-stream - is becoming increasingly popular.

Parameter	x-axis	y-axis	z-axis
Proof Mass [μg]	0.38	0.26	0.39
Natural Frequency [kHz]	3.2	4.2	8.3
Sense Capacitors [fF]	101	78	322
Noise Floor [mG/rt-Hz]	0.11	0.16	0.99
Dynamic Range [dB]	84	81	70
Bandwidth [Hz]	100	100	100
Full Scale [G]	+/-11	+/-11	+/-5.5

Table 1: Performance parameters of a three-axis, fully integrated accelerometer (after Lemkin[15]).

More recently multi-axis accelerometers have been produced; a commercial dual-axis device is the ADXL202 (*Figure 3*) which measures acceleration along the two in-plane axes. Three-axis devices have been described[15] but are still at a prototype stage. As a state-of-the-art example, the specifications of reference[15] are summarised in *Table 1*.

An alternative approach is to use a resonator whose resonant frequency change is dependent on acceleration. The advantage is that a frequency output is a quasi-digital signal which can be easily measured by a frequency counter. Devices with sensitivities as high as 700 Hz/g have been reported[16].

Micromachined gyroscopes

Micromachined gyroscopes typically rely on the coupling of an excited vibration mode into a secondary mode due to the Coriolis acceleration (vibratory rate gyroscopes). The magnitude of oscillation in the sense mode provides a measure of the input angular velocity. These devices require no rotational parts which would need bearings, and hence can be miniaturised relatively easily. In principle the same classifications as for accelerometers can be made.

Gyroscopes are much more challenging devices and most are still under development. Currently it is not clear which approach will be dominant for future commercial devices. One difficulty is that the sensing element must be able to move and hence be controlled in two degrees of freedom: one for the excited or driven mode; the other for the sense mode. One way of describing a micromachined gyroscope is that it acts as a resonator in the drive direction and as an accelerometer in the sense direction. Since the Coriolis acceleration is proportional to the velocity of the driven mode, it is desirable to make the amplitude and the frequency of the drive oscillation as large as possible. At the same time it has to be ensured that the frequency and amplitude remain constant since even very small variations can swamp the Coriolis acceleration. For amplitude control typically an automatic gain control loop is used; frequency stability can be ensured by a phase-locked loop.

As already mentioned, the coupling from the sense to the drive mode by the Coriolis force is very weak, therefore mechanical amplification is often employed. Both the drive and sense mode can be described by a second-order transfer function (a mass-damper-spring system). The dominating damping mechanism is due to the proof mass moving in air. If the proof mass is operated in a vacuum, systems with very-high-Q (several 10,000) can be realised. If the resonant frequencies of the drive and sense mode are matched, the coupling is effectively amplified by Q.

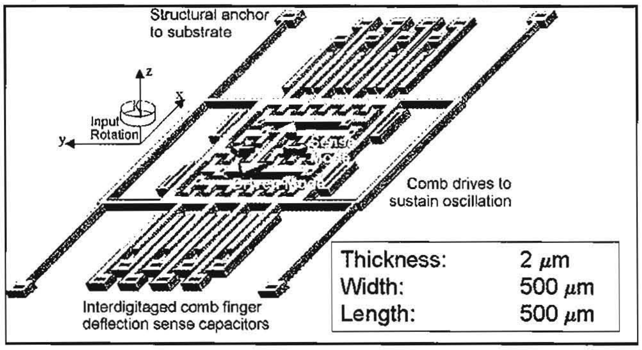

Figure 4: Sensing element for a gyroscope in surface-micromachining technology (after Clark[17]).

The difficulty is to design the two resonant frequencies to match precisely (better than 1 Hz) over the operating temperature range and other environmental influences. The tolerances in the mechanical fabrication process are far too high, hence active tuning is normally used. This relies on applying electrostatic forces on the proof mass which effectively acts as a negative spring constant, and hence can be used to lower the overall spring constant of either the drive or sense mode. With this active tuning method it is still challenging to maintain precise tuning over the operating range of a gyroscope, and considerable research effort is being made to solve this problem.

Another problem is the so-called quadrature error which originates from an unavoidable misalignment of the drive mode from the ideal direction. This produces a signal in the sense mode which can be orders of magnitudes larger than the Coriolis signal. It can be shown that these two signals are usually 90o out of phase and consequently can be distinguished by further signal processing. This assumes that all building blocks operate in the linear region; however, even for small misalignments, quadrature error can cause the sense electronics to saturate. Consequently it is desirable to suppress quadrature error at its origin, which can be achieved by applying electrostatic forces to the proof mass[17].

Both surface- and bulk-micromachined vibratory rate gyroscopes have been demonstrated. One common design (*Figure 4*) is a proof mass which can move along the two in-plane axes by a suspension system comprising two orthogonal bending beams. The drive mode is excited by electrostatic forces using an interdigitated comb drive[18], which has the advantage that the force is independent of the position since the force is generated by fringeing fields. The drawback is that the forces are relatively weak.

Other designs use the out-of-plane axis for the sense mode[19]. Most prototypes reported so far are open-loop in the sense mode; a more recent device uses force-feedback based upon sigma-delta modulation, which results in the same advantages as for the accelerometers[20]. A slightly different approach uses two mechanical structures, one is resonated and couples energy into the second structure whose motion is then detected. A very interesting example[21] has recently been developed further into a commercial product by Bosch. One of the highest performance devices was reported by Draper Labs[19] with a 0.002°/s/rt-Hz noise-floor and a bias stability of 10-100°/h. This is sufficient for many applications, but better performance is still required for navigation-grade sensors.

Another alternative is based on a ring (or wineglass) structure[22]. This is a highly symmetrical design and hence has advantages regarding unwanted cross-axis coupling. The structure is excited by electrostatic forces at four points positioned at 90° to each other, with the two opposing points excited in anti-phase to the other pair. The points on the 45° diagonals remain stationary (nodal points); with the presence of an angular input signal, these nodal points shift which can be detected by capacitive detection.

Silicon Sensing Systems (a joint-venture between British Aerospace Systems & Equipment and Sumitomo Precision Products[23]) is producing a very successful commercial product based upon a wineglass sensing element. However, it uses magnetic actuation and detection which may prove to be problematic for further device size reduction. This gyroscope has a resolution of 0.005°/s, a bandwidth of 70 Hz and a noise floor of <0.5°/s in a 65 Hz bandwidth.

It is also possible to design dual-axis angular-rate gyroscopes by fabricating a disc-shaped structure which is resonated in an angular motion[24]. The device starts to oscillate in the out-of-plane direction for input angular rate signals about the two in-plane axes. One major problem is the cross-axis sensitivity which is reported to be in the range of 16%.

Novel approach to inertial sensing

A radically different approach to inertial sensing is the use of electrostatic levitation which has hardly been exploited for micromachined devices, although it has many inherent advantages over the prevailing concepts[25].

At the Microelectronics Centre, Southampton University, a micromachined disc, levitated by electrostatic forces and with no mechanical connection to the substrate, is currently under investigation. The disc is encaged by electrodes on each side, to which voltages are applied so that the disc is levitated at the centre position parallel to the substrate. Measuring the capacitances formed between the electrodes and the disc can be used to determine the position of the disc. The voltages, required to produce a net electrostatic force on the disc to cancel all external inertial forces, provide a measure for acceleration along the three axes. Since the effective spring constant merely depends on the applied electrostatic forces, it can be adjusted by simply changing the applied voltages; hence the sensitivity and bandwidth can be dynamically altered according to the required specification the sensor is used in. The control system comprises a multi-mode sigma-delta modulator. The device is shown schematically in *Figure 5*.

At the moment efforts are being made to design and fabricate a three-axis accelerometer. However, the project's ultimate goal is to realise a gyroscope with this approach. Several advantages over vibratory-rate gyroscopes are envisaged: quadrature error is inherently ruled out with this design. The comparable effect, due to an unavoidable imbalance of the mass, will manifest itself at the rotation frequency whereas the Coriolis force will cause the disk to precess at the rotational speed of the body of interest. These two frequencies are several orders of magnitude apart and hence easy to separate. Furthermore, there is no need to tune the drive and sense resonant frequencies as required for vibratory-rate gyroscopes for high-Q systems. Initial calculations have revealed that the proposed device should be more sensitive than vibratory-rate gyroscopes; the scale factor is mainly dependent on the rotation speed, which is only limited by the material strength and thus can be made very high. In addition, since the mechanisms to measure angular and linear motion are decoupled, it is possible to design a device that measures these quantities simultaneously - which cannot be achieved with micromachined sensors described in the literature to date. Initial modelling work has already been undertaken and has confirmed the theory[26].

Conclusions

Micromachined accelerometers have established themselves in a variety of commercial devices with a range of different specifications. Most devices use capacitive sensing, but piezoresistive sensing is still being used. Open-loop devices dominate for low-performance devices, whereas force-feedback sensors are used for high-performance applications. Accelerometers with low and medium performance are readily available at a cost level below £5 per axis. Inertial-grade devices have been reported but still need to be further characterised. Both bulk and surface micromachining sensors are available, but it is not clear whether in the near future one approach will become dominant. It is more likely that many different technical implementations will co-exist for the foreseeable future since the requirements are too application specific and span too broad a range for one technology to over.

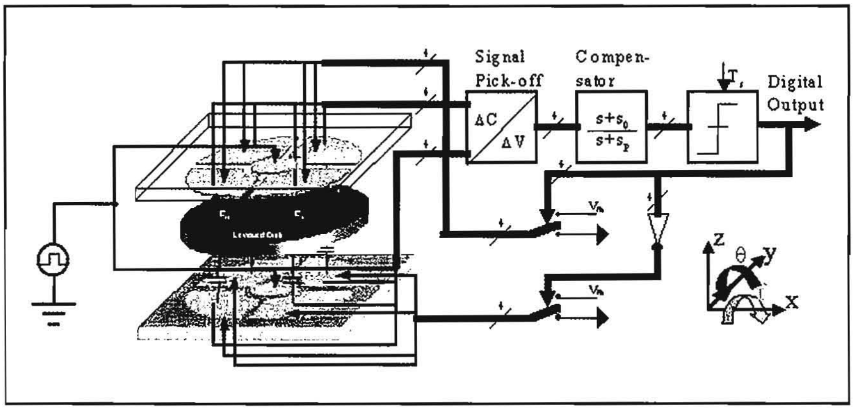

Figure 5: Levitated disc and control system.

Micromachined gyroscopes are still in an early development phase and there is a series of problems for which no satisfactory solution has yet been found. It is not clear which approach will manifest itself as a *de-facto* standard. Nevertheless, the first commercial devices for low-to-medium-performance applications are already available and their number will grow considerably in the near future.

A novel approach based upon electrostatic levitation promises to overcome some of the drawbacks of vibratory-rate gyroscopes. The first prototypes, currently under development at the Microelectronics Centre, are expected to be available this year.

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